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Arc Hydro Developments for the Lower Colorado River Basin

by

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Chapter 1: Introduction

1.1 BACKGROUND

A geographic information system (GIS) provides an effective method for managing, viewing, and editing spatial data. Hydrology is the study of the movement of water throughout the Earth, and it is generally spatial in nature. Therefore, the merger of hydrology with GIS is a natural goal for many watershed analysts. Over the past decade, this goal has been proven both possible and effective for a variety of analyses including flood studies, water quality studies, and water rights management.

A "hydrologic information system" results from the synthesis of time series, geospatial data (GIS data), and hydrologic modeling and analysis (Maidment, 2002), as illustrated in Figure 1.1. It is important to realize that such a system contains two different types of models. A "data model" is used to store important geospatial and time series data within a standardized framework; and a "computational model" (or "simulation model") contains the algorithms necessary to simulate natural processes. Therefore, a hydrologic information system combines the predictive capabilities of a computational model with the data management capabilities of a data model.

Arc Hydro, which was developed by the Center for Research in Water Resources (CRWR) at the University of Texas in Austin, is a data model for storing general hydrologic geospatial and time series data. A standardized data model is important because it allows for interoperability between various water agencies, and it provides a framework around which for future computational programs can be designed. Therefore, many water agencies are now interested in converting their water resources data into an Arc Hydro compliant form.

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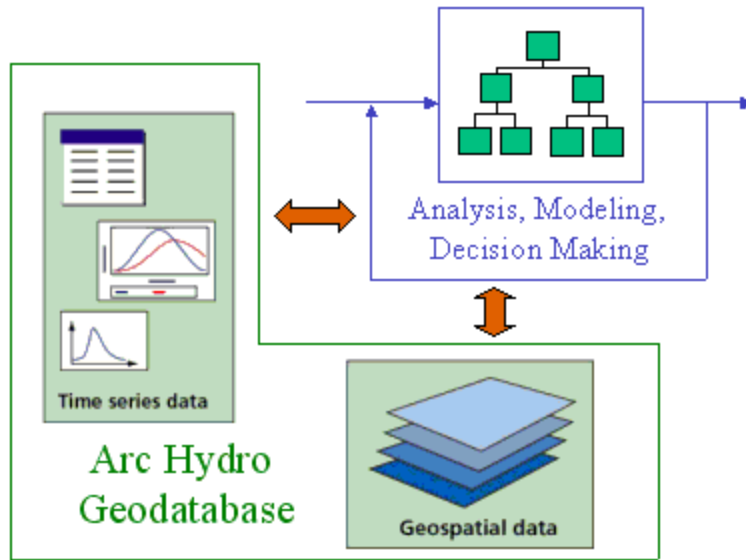
Figure 1.1 – Hydrologic Modeling System (Maidment, 2002)

The Lower Colorado River Authority is the agency that regulates the Texas Colorado River System from Lake O.H. Ivie to the Gulf coast, as shown in Figure 1.2. One of the organization's primary responsibilities is management of the Colorado River floodplain. This responsibility includes determining the flood risk associated with various structures located along the river. The LCRA also attempts to minimize flood damages during storm events through the careful operation of the river system's dams and reservoirs. To assist in this work, the LCRA maintains an extensive collection of geospatial and hydrologic time series data for the river basin. The LCRA also maintains a set of hydraulic and hydrologic computational models (H&H models) that help to predict the river's water surface elevation profile during rain events.

Figure 1.2 – Lower Colorado River site map (adapted from LCRA website)

1.2 STUDY OBJECTIVES

The purpose of this research was to determine how Arc Hydro could be applied to the hydrologic data and computational models of the LCRA. Through a collaborative effort, CRWR and LCRA developed a series of project objectives that have helped guide this research. A summary of these objectives is as follows:

1. Review of the LCRA's existing computational models and data.

2. Creation of a prototype Arc Hydro data model for the Llano River Watershed (a tributary area of the Colorado River Basin), including relevant time series data.

3. Development of an "Interface Data Model" that will act as an interface between Arc Hydro and the hydrologic program, HEC-HMS.

4. Development of a system for generating floodplain maps and determining inundated structures based on H&H model results.

The purpose of item #1 is to provide an inventory of the LCRA's river operations data and models and how they work together. Item #2, the Arc Hydro data model, is important because it provides an organized, connected, and standardized container for the LCRA's hydrologic data. Item #3 creates an archive for storing and viewing the data used in a hydrologic computational program, and it provides a platform for future integration of hydrologic modeling with GIS. Finally, item #4 gives the LCRA an optimized system for comparing the results of different HEC-RAS models, and thus provides a method for comparing different flood control alternatives.

1.3 THESIS OUTLINE

Chapter 2 is a literature review that covers the Arc Hydro data model, flood damage analyses, and other applications involving GIS and water resources. Chapter 3 includes an overview of the existing data and models considered throughout the course of this project. In effect, Chapter 3 accomplishes the first of the project objectives (as listed in the previous section). Chapter 4 presents the methodologies used to develop objectives two through four. Chapter 5 discusses the results of this research. Chapter 6 includes conclusions and recommendations for future work.

Chapter 2: Literature Review

As discussed in the last chapter, this research involves the connection of hydrologic data and models to GIS. A significant amount of past effort has been put forth to accomplish this goal. This chapter is primarily a review of such efforts, including an introduction to the Arc Hydro data model. The chapter also briefly discusses methods used for calculating economic damages that result from flooding events.

2.1 ARC HYDRO DATA MODEL

The Arc Hydro data model was introduced to the public in 2002. It is the result of three years of development by Dr. David Maidment's research team at the Center for Research in Water Resources (CRWR), The University of Texas at Austin. The Environmental Systems Research Institute (ESRI), maker of the ArcGIS software package, has also played a role in the Arc Hydro design. Throughout the development process, the Arc Hydro concept has held the interest of many public and private water-related organizations. Now that the Arc Hydro data model is available, these organizations would like to employ the model for their benefit. To assist these organizations in implementing the data model, the book "Arc Hydro, GIS for Water Resources" was published by ESRI in 2002.

Arc Hydro is a geospatial and temporal GIS data model that can be used to maintain the water resources data necessary for hydrologic modeling and analysis (Maidment 2002). In general, Arc Hydro was created with three primary components:

1. A standardized format for storing geospatial and temporal hydrologic data.

2. Logical data relationships among geospatial features based on hydrologic principles

3. A set of tools for creating, manipulating, and viewing hydrologic data.

The first two of these components were created using the Unified Modeling Language (UML) to design a standard "Arc Hydro" geodatabase. The Arc Hydro geodatabase includes a number of tables that represent different hydrologic themes. Tables that represent spatial entities, such as watersheds and monitoring points, are called "feature classes". Tables that represent non-spatial data, such as time series, are called "object classes". Inside these tables (or "classes") are standardized field names such as "JunctionID", "HydroCode", and "FlowDir". Fields with an "ID" or "Code" suffix are used for identifying individual hydrologic objects. Fields with the "ID" suffix are integer fields, and fields with the "Code" suffix are text fields. In addition to identification fields, there are also fields that store hydrologic characteristics, such as "FlowDir" (which stores the direction of flow in a stream line) and "AreaSqKm" (which stores the area of a watershed).

Arc Hydro's data relationships were also created using UML. These relationships are used to associate hydrologicaly related entities. For instance, a watershed may be related to an outlet point (to which the watershed drains); and a stream gage may be related to a point along a river; and a set of precipitation records may be related to a rain gaging station. With these relationships established, the user may easily query related hydrologic information.

The third component of Arc Hydro is the Arc Hydro Toolset, which runs within the ArcMap environment. This toolset can be used for a number of hydrologic processing routines including raster processing and the assignment of feature attributes.

Furthermore, Arc Hydro makes use of a number of other ArcGIS toolsets including ESRI's Spatial Analyst and Network Analyst.

GIS Data Types Used by the Arc Hydro Data Model

The two most common types of GIS data are raster and vector. Vector data include points, lines, and polygons and their associated attributes. Vector data is ideal for representing streams, watersheds, and monitoring points. The Arc Hydro is made up almost entirely of feature classes, which are vector data. Rasters are gridded data, where each cell of a raster grid possesses one unique value. Raster data are not typically considered to be a part of the Arc Hydro data model. Raster data can, however, be used to generate vector data used by the Arc Hydro model. In fact, much of the Arc Hydro toolset focuses on using land surface elevation rasters to generate streams and catchments for the data model.

Three Versions of the Arc Hydro Geodatabase

To accommodate the varying demands of Arc Hydro users, three different versions of the Arc Hydro Geodatabase were created. They contain many of the same tables and field names, and only vary in their level of complexity. They are described below:

1. Arc Hydro Framework – contains only the feature classes that are necessary to create a useable Arc Hydro flow network (watersheds, rivers, junctions, waterbodies, and monitoring points).

2. Arc Hydro Framework with Time Series – contains all of the classes found in the Arc Hydro Framework, plus tables for storing time series data.

3. Arc Hydro Full Model – contains all of the classes found in the Arc Hydro Framework with Time Series, plus additional classes that describe river schematics, channels, and flow exchange points.

These three versions are not rigid; they can be modified to fit the needs of individual organizations. This research involved the "Arc Hydro Framework with Time Series" data model. However, the concepts discussed in this report apply equally to all three models. A diagram of the Arc Hydro Framework with Time Series is shown in Figure 2.1.
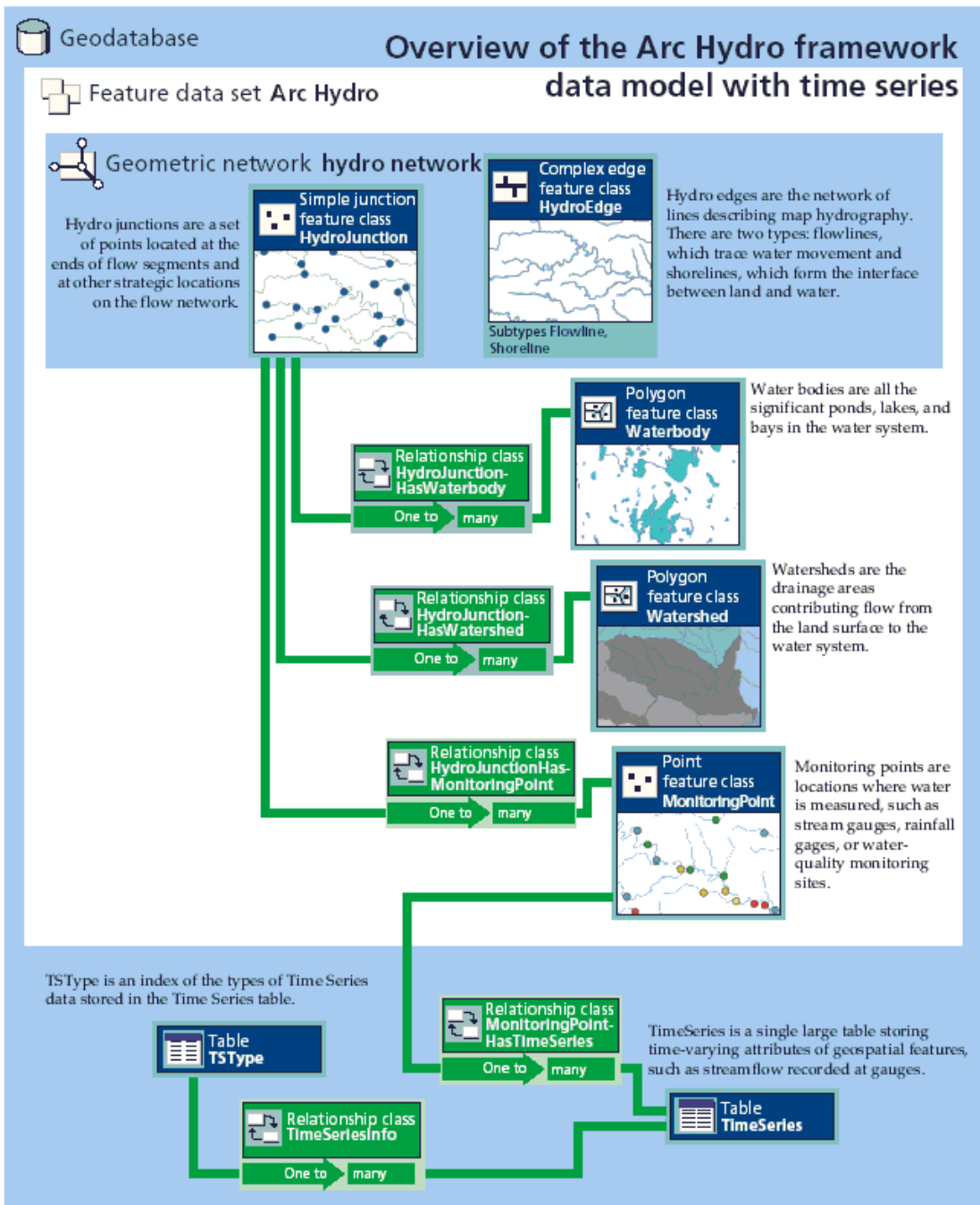
Figure 2.1 – Arc Hydro Framework with Time Series (Maidment, 2002)

2.2 OTHER GIS APPLICATIONS FOR HYDROLOGY

While Arc Hydro has helped to formalize the concepts essential to connecting GIS with hydrologic modeling, it is not the beginning or the end of this development process. For instance, it should be emphasized that Arc Hydro is a data model, and further development is generally required to connect it with computational (simulation) models:

> Arc Hydro is a data structure that supports hydrologic simulation models, but it is not itself a simulation model. Hydrologic simulation is accomplished by exchanging data between Arc Hydro and an independent hydrologic model, by constructing a simulation model attached to Arc Hydro using a dynamic linked library, or by customizing the behavior of Arc Hydro objects. (Maidment, 2002)

How tightly to couple GIS and computational models is an important consideration when designing a hydrologic information system. A loose coupling means that the necessary hydrologic data is stored both by the GIS and the computational model, and that the data must be passed back and forth between the two. A tight coupling means that the data for the GIS and computational model share the same database, and possibly even the same "manipulation framework" (McKinney and Cai, 2002).

A tightly coupled hydrologic information system is advantageous because it requires less data transfer, and it can be more easily managed by a single user interface such as ArcMap. In such a system, the geographic information system may: (1) prepare the necessary computational model data, (2) have the ability to compile this data into model input files, (3) run the computational model, and (4) present the models results (McKinney and Cai, 2002).

Some computational models, however, are of such a complex design, that it may prove cumbersome to tightly couple them to a GIS. In these cases, the GIS is often only used for preprocessing or post processing of the data required by the computational model. In the case of GIS preprocessing, the modeling data is created as part of a GIS

database, and then transferred to a computational model database. CRWR-PREPRO was one of the first systems developed to perform hydrologic preprocessing. This GIS program, which was the predecessor of HEC-GeoHMS, could derive input files for the hydrologic modeling program, HEC-HMS (Hellweger, 1999).

More recently, a number of specialized data models have been developed around the more general Arc Hydro data model. These data models are specific to particular computational programs, but were developed using the Arc Hydro model as a template. Thus, these data models often share data structures and naming conventions similar to that of Arc Hydro. One such model, BASINS Hydro, was designed to store the data found in the Environmental Protection Agency's Better Assessment Science Integrating Point and Nonpoint Source (BASINS) program. This data model was designed primarily for viewing and analyzing the data found in the BASINS database. This project also presented the concept of creating a data model that incorporates two or more geodatabases, so that the data may be handled more efficiently (Schneider, 2002).

A GIS preprocessor and data model for the Texas Water Rights Analysis Package (WRAP) has also been developed. The WRAP Hydro data model was designed based on Arc Hydro principles and stores the data necessary to run the WRAP program. Also of interest, the WRAP Hydro model makes use of the data and tools included in the more general Arc Hydro model (Gopolan, 2003).

2.3 FLOOD DAMAGE STUDIES

A long-term goal of this research is to find ways of making flood mapping and damage analysis more efficient, and possibly even more accurate. Over the past decade, the use of GIS in flood mapping applications has greatly increased, but GIS methods for determining flood damages (economic dagames) are still not well established. The existing methods used to determine flood damages are based on procedures developed by

the U.S. Army Corps of Engineers. These procedures are quite elaborate, and a thorough review of them would be beyond the scope of this research. Nonetheless, it is interesting to examine how a GIS-based system could offer advantages over the traditional methods of damage analysis.

In 2000, the National Research Council (NRC) published "Risk Analysis and Uncertainty in Flood Damage Reduction Studies". Among the material in this report is an outline of the procedures used by the U.S. Army Corps of Engineers when estimating flood damages. The report also discusses the limitations in these procedures and makes recommendations regarding how they might be improved. Under the current system, the Corps aggregates structures and damages over "damage reaches". In this system, a graph relating total economic damage to river stage is calculated for each reach. According to the NRC report, aggregating the structures in this way can lead to inaccuracies when considering the uncertainties associated with various flood control alternatives. Therefore, the NRC report recommends that damage analyses be conducted on a structure-by-structure basis. Similarly, the report recommends that levee performance should be evaluated as a spatially distributed system.

Using GIS to automate the flood map production process has been found to have many advantages over the traditional, manual methods of floodplain delineation. Automated delineation procedures can potentially improve map accuracy, as well as the speed of map generation (Noman, 2001). GIS floodplain delineation requires two primary inputs: a land surface layer and a water surface layer. Inundation occurs wherever the elevation of the water surface layer exceeds the elevation of the land surface. To ensure quality flood maps, the land surface data must be of sufficient accuracy and resolution. Triangular irregular networks (TINs) and grids (rasters) are the two primary methods for representing land surfaces. TINs are more effective for

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capturing small details in the land surface, however, rasters can usually be processed at a faster rate. Care must also be taken to ensure that the generated water surface layer (interpolated from hydraulic model results) is an accurate representation of flood conditions. In general, the further removed from the centerline of the hydraulic model (assuming a one-dimensional model), the more difficult it is to predict water surface elevations. Water surface layers generated from cross sections with assigned flood elevations tend to be more accurate than water surface layers generated from individual flood point elevations. Also, in many cases, it is important to account for natural and man-made barriers to water flow when determining the water surface layer (Noman, 2001).

2.4 SUMMARY OF EXISTING RESEARCH

Arc Hydro has the capability to store the general data that describes a hydrologic system. In addition to Arc Hydro, a number of more specific GIS data models have been developed to store the contents of particular hydrologic computational programs. These data models have demonstrated the effectiveness of managing and analyzing data from within the GIS environment. Furthermore, many of these data models have associated tools for the creation and processing of relevant hydrologic data. However, the existing data models do not, generally, provide a thorough coupling of GIS with computational modeling. Most of the existing data models do not store all of the data required to run their associated computational models, and little effort has been put forth to create a system that can continually pass data back and forth between the computational model and GIS.

Chapter 3: Data and Models Review

The previous chapters discussed how GIS data and computational models may be synthesized into hydrologic information systems. This chapter discusses the details of the data and models used at the LCRA. Extra attention is given to those data and models that were central to the objectives of this research.

3.1 GIS DATA

The Lower Colorado River Authority is a large organization with considerable data needs. The LCRA runs the Colorado River dams, a series of power plants, transmission lines, and local water systems. Because of these responsibilities, maintaining a set of quality GIS data is very important to the organization. Of particular interest to this project is the LCRA's existing hydrologic data.

Much of the LCRA's GIS data resides on a Microsoft SQL Server that is known to its users as "LCRA World". The LCRA World stores over one hundred GIS files, many of which are related to hydrology. These data include rivers, lakes, bridges, dams, gaging stations, watersheds, high water marks, and aquifers. A complete listing of files stored in the "LCRA World" is included in Appendix A.

In addition to the LCRA World, the LCRA maintains a considerable amount of GIS data that are specific to particular projects or computational models. Often, these data are maintained by particular individuals or departments within the LCRA. Since these data are not available on the LCRA World, only certain employees have access to them. The GIS results of hydrology and hydraulic studies are typically stored in this manner. Model-specific data particularly relevant to this research project is discussed in greater detail in Chapter 4.

3.2 HYDROLOGIC AND HYDRAULIC MODELS

A primary mission of the LCRA's river modeling staff is to perform flood simulations. These simulations can either be run using real-time or historical (archived) data. Real-time data are used when modeling current storm events. Historical data are used for calibration and to determine statistical flood information, such as 100-year floodplain elevations. In either case, it is computer-based hydrology and hydraulic (H&H) models that are used to calculate the results.

Typically, separate software programs are used for hydrology and hydraulics. The hydrology program is run first, and calculates stream flows based on precipitation and watershed characteristics. The hydraulic program is run second, and calculates floodplain elevations based on stream flows (typically calculated by the hydrology program) and river channel characteristics.

For real-time flood modeling, the LCRA uses an automated set of US Army Corps of Engineers, Hydraulic Engineering Center (HEC) modeling programs. The hydrology program is HEC1 and the hydraulic program is UNET. Both of these programs are relatively old, and are no longer under development at the HEC. Because speed is an important factor for real-time modeling, the LCRA contracted with a private consulting firm to automate and build a user-friendly interface for these programs. The resulting application is called the Catchment Forecasting System (CFS).

The LCRA plans to replace CFS with a more modern system in the near future. The HEC's Corps Water Management System (CWMS) is the program the LCRA has selected for this purpose. This system was developed by the HEC specifically for use at the Corps' district and division offices (HEC, 2003). The system includes programs for hydrology, reservoir operation, river channel hydraulics, and flood analysis (but not flood

mapping). More recently, the Corps has attempted to market this system to large water management agencies such as the LCRA.

For historic flood modeling, the LCRA uses a set of HEC models developed by the consulting firm Halff & Associates. CRWR also played a role in this project by delineating a set of watersheds for use in the hydrology model (Stone, 2001). The hydrology program is HEC-HMS, and the hydraulic program is HEC-RAS. After calibrating these models, Halff and Associates used them to perform an extensive review of floodplain elevations resulting from various return-frequency storms (Halff, 2002). Figure 3.1 shows the spatial extent of the LCRA/Halff modeling effort. It is anticipated that these models will also be incorporated into the LCRA's new flood forecasting system (CWMS).
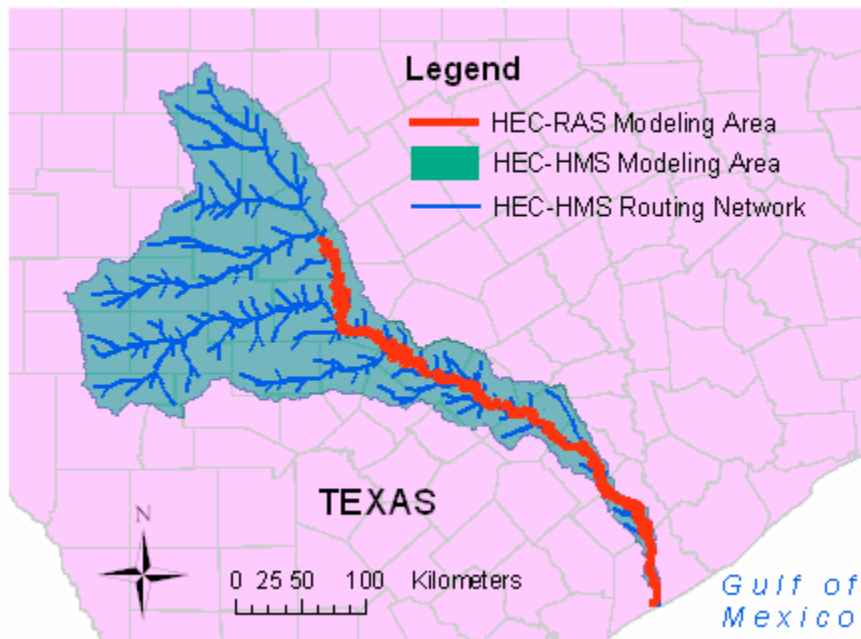
Figure 3.1 – LCRA/Halff H&H modeling effort

3.3 INTRODUCTION TO HEC-HMS

The HEC's Hydrologic Modeling System (or HMS for short) was very central to this research effort, and a thorough understanding of this program was essential. Generally, the input to HMS is precipitation, and the output is flow. This conversion takes place using a model of the river basin in question. The primary basin elements are subbasins (watersheds) and reaches (streams). Precipitation is converted to run-off over the subbasins, and the run-off is then routed through the reaches, providing storm flows at locations along the stream network.

HMS is a somewhat complex program that provides many options for calculating run-off and flows. These options include a variety of different methods for determining base flows, loss rates, transforms, and routing. In addition to this, there are a number of methods available for distributing precipitation, and HMS can perform these calculations over gridded (spatially distributed) or lumped (catchment) basins. Furthermore, a given HMS project can store information for multiple storm events and multiple basins. And finally, HMS has an elaborate scenario-control structure capable of keeping track of all of these options.

A typical HMS project includes a number of data files and control files. With the exception of time series and paired data, most HMS data are stored in text files, which can be easily viewed and edited by the user (however, the manual editing of text files is not necessary since HMS comes with a standard Windows graphical user interface (GUI)). Time series and paired data are stored in the HEC's Data Storage System (DSS). This is a binary system, and it is not easily edited without the aid of specialized HEC software. Nonetheless, it is an effective storage system because it is compact in size and allows quick data queries. The most common and important HMS file types are shown in Table 3.1.

The DSS file is the central repository for both input and output data. Figure 3.2, which was created as part of this project, presents a conceptual view of the HMS file structure and also shows the flow of DSS data through HMS. The DSS data used in a given scenario (run) are selected based on the control and meteorological files, and then processed using the parameters found in the basin file. The results of the run (flow hydrographs) are returned to the DSS file for storage.

File Extension	Files per project	Description
hms	1	list of basin, met, and control files
dss	1 or more	time series and paired data
dsc	1 or more	catalog of dss file
gage	1	defines all project gages
run	1	defines all project run scenarios
control	1 per storm event	defines timing information for event
basin	1 per basin model	basin model information
met	1 per met model	meteorological model information

Table 3.1: Common HMS file types and descriptions
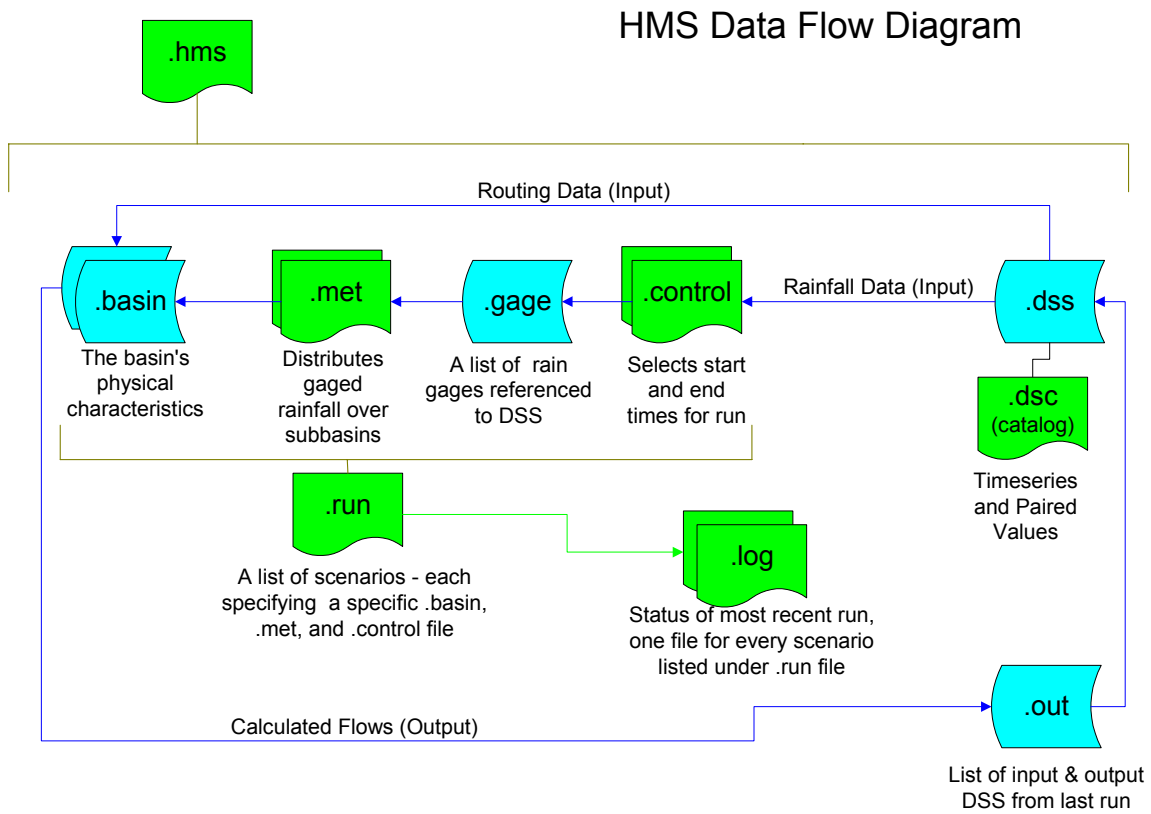
Figure 3.2 – HEC-HMS flow diagram – data storage files in blue, control files in green

HEC-GeoHMS

HEC-GeoHMS is the HEC's system for GIS preprocessing of HEC-HMS input data. The current version of HEC-GeoHMS is limited because it only works with the older (though still used) ESRI ArcView 3.2 software. However, a newer version of HEC-GeoHMS is currently under development. GeoHMS uses shapefile and raster input data to generate HMS input files, including a base map, lumped or distributed (gridded) basin model, and a grid cell parameter file. This program is not typically used at the LCRA.

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3.4 INTRODUCTION TO HEC-RAS

The HEC's River Analysis System (HEC-RAS or RAS) is not as central to this research as HEC-HMS, but it is still important to have an understanding of how the program operates. RAS calculates river stage elevations based on flow data and river channel characteristics. Flow data can be obtained from river gages or from hydrologic program results. Channel data are defined in terms of cross sections and are typically generated from survey or digital terrain data. The RAS file structure is quite complex, but like HMS, all file manipulation is typically handled through the program's GUI. Like HMS, time series data are stored in DSS files, though in a somewhat different format. HEC-RAS model results can be exported using a number of methods, including an SDF text file, designed specifically for GIS applications. This file includes the location, geometry, and calculated water surface elevation for each RAS cross section.

HEC-GeoRAS

HEC-GeoRAS is the GIS processing program for HEC-RAS. As with HEC-GeoHMS, the current version of HEC-GeoRAS only works with the older ESRI ArcView software. However, an ArcGIS beta version, under development at ESRI, has been released to CRWR for testing. The HEC-GeoRAS system is used as both a preprocessor and a postprocessor. As a preprocessor, HEC-GeoRAS is used to calculate river channel geometry data. As a postprocessor, the program calculates flood inundation maps. This program is sometimes used at the LCRA for floodplain map generation.

3.5 TIME SERIES DATA

LCRA Hydromet System

For H&H modeling, the primary time series inputs are stage, stream flow, and rainfall data. At the LCRA, these data are collected though the "Hydromet" system. The

term "Hydromet system" encompasses many things. First of all, the Hydromet is a series of gages that measure stream flow, rainfall, and other data throughout the Lower Colorado River Basin. Second, the Hydromet includes a system that collects and transfers (polls) these data. Finally, "Hydromet" is also the name of the database where these data ultimately reside.

Data are polled from the gaging stations approximately once every hour under normal conditions, once every half-hour during storm events, and manually as needed. Once the data are polled, they are transferred into the Hydromet database. In this database, every poll is recorded as a unique time series record. The record includes the date and time of the poll, the ID of the sensor (gage) that was polled, the data type, the data's source, a comment, and two values. Having two values is important for the LCRA's stream flow and rainfall data. A stream flow record stores a stage value and flow value (based on a rating curve), and a rainfall record stores a counter value and an incremental rainfall value (rainfall is calculated based on the number of times a tiny scoop fills and tips within a tipping-bucket rain gage).

The structure of the Hydromet database is somewhat complex, and it is diagrammed in Appendix B. The primary time series table is called "Datachron", which contains a complete history of Hydromet records. In addition to Datachron, there are a series of smaller time series tables that store records over short time periods of specific interest (i.e. the table "Data_Recent" stores the latest two weeks of Hydromet records). Because of their limited size, these small time series tables can be queried and manipulated more quickly than the larger "Datachron" table. Records in the time series tables are related to a "SensorDef" table that stores information about the instrument that took the reading. The SensorDef table is related to a "Site" table that stores information about the location where the sensor (instrument) is located. Datachron, SensorDef, and

Site make up the primary Hydromet time series data structure. However, there are other miscellaneous tables, most of which are shown in the Hydromet diagram located in Appendix B. It is important to note, however, that the LCRA does not fully populate this database. Many fields are left empty. According to Chris Riley, an LCRA hydrologist, (personal communication, 2003) some of these empty fields may be used in the future. Also, however, the LCRA is currently considering upgrading the Hydromet, and this could result in a different database structure.

For the purposes of H&H modeling, it is best to have regular interval time series data. This is not accomplished in the Datachron table because the original data polls do not occur exactly at even one-hour intervals. Therefore, regular one-hour interval data must be calculated through interpolation, and stored in a separate location from the raw data. In the Hydromet system, the "Interval" table is used to store this regular data.

In addition to Hydromet gages, the LCRA also makes use of radar-generated rainfall maps. Although these maps are effective for viewing the spatial distribution of rainfall, they are not always accurate in the total volume of rainfall they predict. Therefore, radar generated rainfall is usually calibrated using physical rainfall gages. The LCRA has out-sourced the radar data collection and calibration process to a private firm – the NEXRAIN Corporation. NEXRAIN calibrates the radar rainfall maps based on data they receive real-time (one-hour time interval) from the LCRA's Hydromet rainfall gage system. According to LCRA engineer, Daniel Yates, about twenty minutes elapse between the time the LCRA sends their gaged data to NEXRAIN, and the time the calibrated rainfall data are sent back to the LCRA (personal communication, 2003).

NEXRAIN stores radar-generated rainfall data on a 2km x 2km grid, but this is not directly applicable to the LCRA's "lumped" hydrologic model (the HEC1 component of CFS). To accommodate this difference, NEXRAIN lumps the gridded rainfall data

onto the LCRA's HEC1 watersheds. After being sent to the LCRA, these lumped rainfall data are stored as "virtual rain gages" in the Interval table. The Interval table is then used to drive the CFS real-time flood-forecasting model. An example of lumping gridded rainfall data onto watersheds is shown in the Figure 3.3.
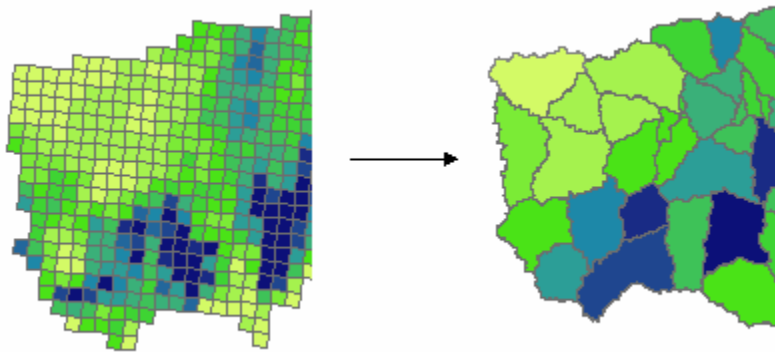
Figure 3.3 – Transferring gridded rainfall data to watersheds

In general, the LCRA's river modeling engineers rely on a continuous feed of rainfall and stream flow data to drive their real-time models. The results of their modeling efforts include reservoir elevations, stream stages, and flows. A diagram, detailing this flow of data, is included in Appendix C.

LCRA Water Quality Data

Although hydrologic and hydraulic modeling data are the primary focus of this project, water quality data have also been examined. One of the reasons for this examination is that the Arc Hydro data model may eventually be used not only by the river modeling department, but by the entire LCRA. Other divisions of the LCRA that have an interest in Arc Hydro include the water resources management group and the water quality management group.

The LCRA began collecting water quality data as a service to the Texas Commission on Environmental Quality (TCEQ). By doing this, the LCRA agreed to follow the TCEQ format for archiving water quality data, which is diagrammed in Appendix D. The LCRA also uses these data to perform water quality modeling throughout the basin. However, unlike the CFS H&H system, the water quality models do not pull data directly from a database. Instead, the data are manually queried and exported from the water quality database in the form of flat-files (text files). The flat-file often has to be modified into a format that is acceptable to the water quality modeling program.

Chapter 4: Methodology

The previous three chapters covered the background of this research project. This chapter discusses the methodologies used to accomplish the project's objectives. There are three primary sections in this chapter: (1) Arc Hydro Framework with Time Series Development, (2) Interface Data Model Development, and (3) Flood Damage Evaluation System Development.

4.1 POPULATING THE ARC HYDRO FRAMEWORK

Building an Arc Hydro data model requires the gathering, compiling, and modifying of significant amounts of data, often from unrelated sources. For this project the data discussed in Chapter 3 were the primary data used in the Arc Hydro model. During the development, these data were modified and related to each other to form a complete and connected picture of a prototype river basin.

4.1.1 Llano River Background Information

To determine the applicability of the Arc Hydro data model to the Lower Colorado River basin, it was determined that a pilot project should be conducted on a portion of this basin. The rational for selecting a portion of the basin, and not the basin as a whole, was that work on a smaller dataset could be performed more quickly, allowing more time to test different design alternatives. Furthermore, the procedures and results developed by the pilot project can be used as a guide when applying Arc Hydro to the entire Lower Colorado River Basin.

The Llano River Basin was chosen for this pilot project because it is a well-known, moderately sized tributary of the Colorado River System. The north and south branches of the Llano River begin in the central Texas hill country, about 45 miles (72

km) west of the town of Junction. At Junction, the two branches merge together into one river. From Junction, the river continues to wind its way east-northeast, until it outlets into the Colorado River just upstream of Lake LBJ. The basin is roughly rectangular, and is approximately 125 miles long by 40 miles wide (200 km x 65 km). A map of the basin is shown in Figure 4.1.

The Llano River is known for the rapid rise of its waters during storm events. During such events, water quickly runs off of the Llano's hard, rocky watershed, making the river a challenge to both monitor and to control. In the summer of 1997 a storm hit the Llano causing the river to surge to over 300,000 cfs, a very impressive event, considering the average flow for the previous year, 1996, was only 70 cfs (LCRA, 1998). Typically, the floodwaters are not subdued until they enter the Highland Lakes. During the 1997 flood, many homes along the Llano River, Pedernales River, Colorado River, and Lake Travis were flooded, but fortunately, no lives were lost.
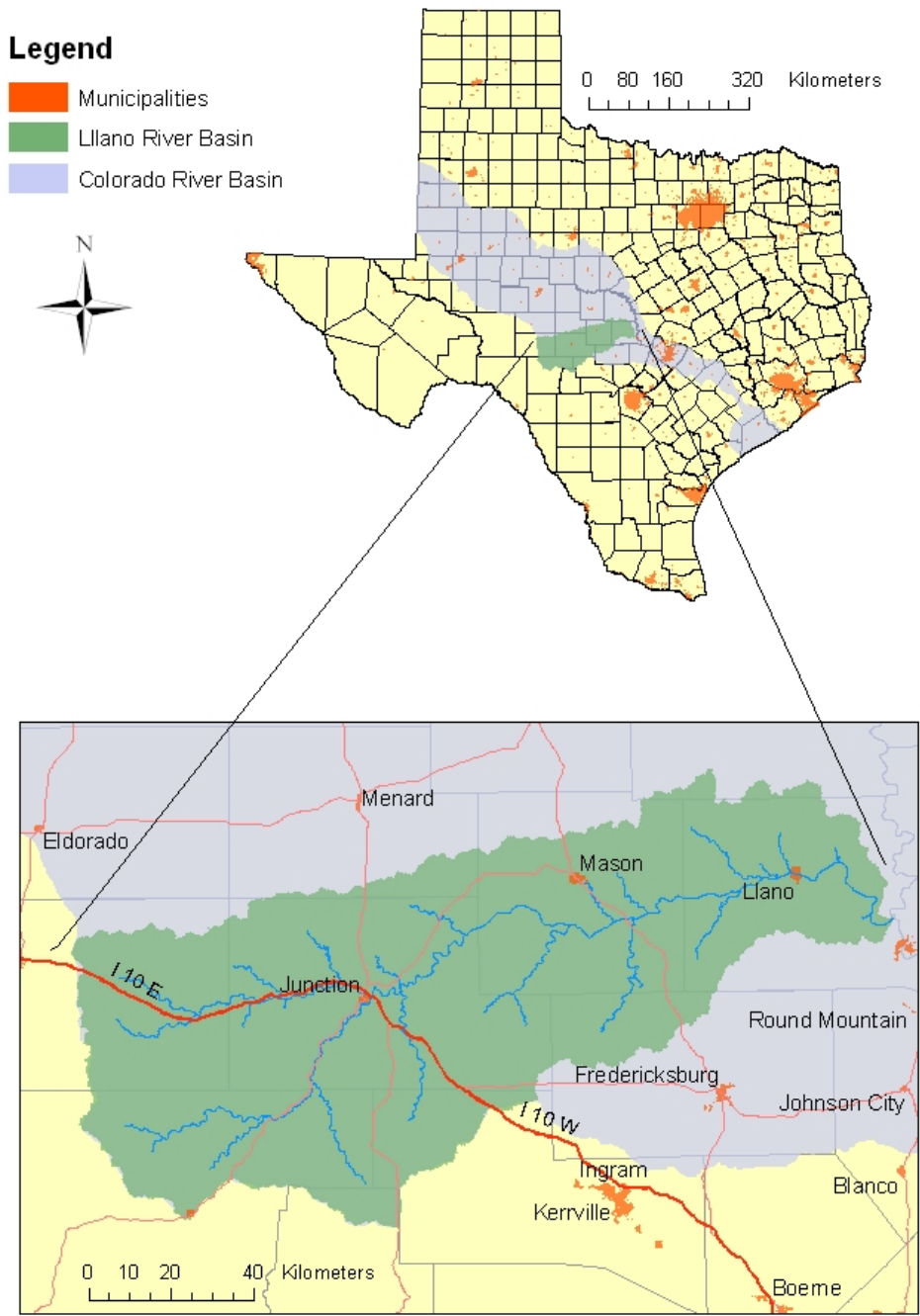
Figure 4.1 – Map of the Llano River Basin

H&H Models for the Llano River Basin

The Llano River is part of the LCRA's CFS real-time flood model. The CFS system includes a simple hydrologic model for the entire Llano Basin. CFS does not, however, include a hydraulic model for the entire Llano River. Only a small stretch of the river (from the City of Llano to the confluence with the Colorado River) is modeled with UNET. This means that flows can be calculated along the entire Llano River, but flood elevations can only be calculated downstream of the City of Llano.

As discussed in Chapter 3, the study by Halff & Associates has provided the LCRA with a new set of H&H models. The Halff hydrologic model for the Llano Basin is much more refined than the CFS hydrologic model. However, as with the CFS system, the Halff system provides no comprehensive hydraulic model for the Llano River. According to Daniel Yates, a LCRA river operations engineer, (personal communication, 2003) there is no comprehensive hydraulic model for the Llano River currently available. The existing UNET model covers only a fraction of the Llano River and it is not very sophisticated (it uses eight-point cross sections). The creation of a more complete model is, however, currently under consideration at the LCRA.

4.1.2 Arc Hydro Raster Processing

Raster processing is an optional, but common first step in Arc Hydro data model development. As discussed in Chapter 2, raster data can be used to generate vector data essential for the Arc Hydro model. The raster shown in Figure 4.2 is a digital elevation model (DEM) for the Llano River basin. This model was created from existing raster data for the state of Texas, available at CRWR. The cell size is 30-meter.
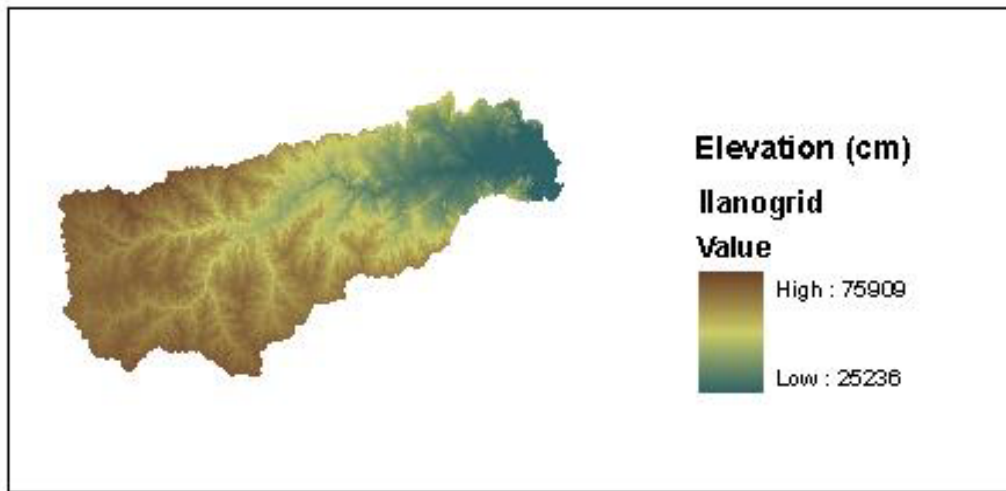
Figure 4.2 – DEM of the Llano River Basin

Raster Processing

The theory behind the raster development process has been well documented in a number of past reports (Stone, 2001), and the tools needed for the process are all available within the Arc Hydro toolset. Most of these tools start with an existing raster, perform an algorithm on the raster, and generate a new raster that contains the algorithm results. A summary of the raster processing tools used for this project is included in the following list. An example of raster-derived vector data for the Llano River basin is shown in Figure 4.3.

1. DEM Reconditioning – modifies the raster to more closely match a set of vector streams.

2. Fill Sinks – modifies the raster by filling pits in the landscape. Pits are a problem because all cells must be able to drain to the basin's outlet.

3. Flow Direction – calculates the direction that water will flow from a given cell. The calculation is based on the slopes between adjacent cells.

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4. Flow Accumulation – calculates the number of cells that are upstream of a given cell.

5. Stream Definition – determines which cells are "stream cells". Stream cells are cells that have a sufficient amount (arbitrarily set) of flow accumulation.

6. Stream Segmentation – divides streams into unique segments. Streams are segmented at locations where they intersect.

7. Catchment Grid Delineation – determines the watershed of each stream segment.

8. Catchment & Stream Vector Processing – converts stream segments and catchments into vector features (shapes and lines).

9. Drainage Point Processing – places drainage points at the intersection of streams and catchments.
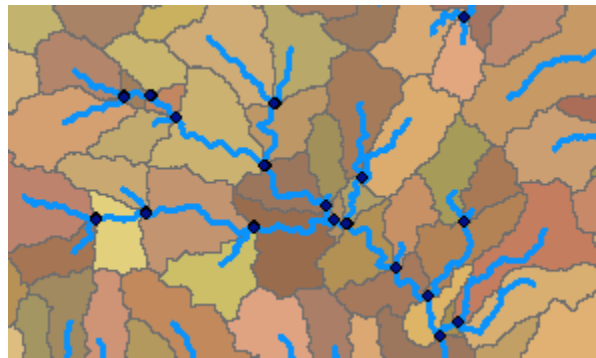
Figure 4.3 – Vectorized catchments, lines, and points for the Llano River Basin

Using Raster Derivatives

Raster derivatives (including vectorized catchments, drainage lines, and points) can serve multiple purposes. All of the derivatives can be used in the Arc Hydro data model. Also, catchments can be used in hydraulic models, such as HEC-HMS, and

drainage lines can be used as rivers in maps. A set of the rasters and raster derivatives for the Llano River Basin can be found in the CD in the back of this report.

4.1.3 The Arc Hydro Framework

Development of the Arc Hydro Framework for the Llano River Basin was a major aspect of this research effort. As discussed in Chapter 2, the Arc Hydro Framework provides a spatial data model that describes basic information about the basin, and around which H&H models and time series applications may be constructed. This section covers the various steps that were followed in order to create the Arc Hydro Framework. It should be emphasized that the procedure outlined in this section is based on methods previously developed by CRWR, but which have been significantly modified by the author to provide the fastest and most efficient development procedure for the data under consideration. A tutorial, developed as part of this project is included in Appendix E, and gives step-by-step instructions for the framework development process.

Step 1. Acquiring Source Data

To build a complete Arc Hydro Framework, one must have GIS data for streams, waterbodies, watersheds, and monitoring points. These data can be obtained from a number of sources. The most common sources for these data are probably the USGS and EPA. Local governments and regional water authorities are also often a source for such data. The vectorized results of raster processing could also be used (for this project, the raster derivatives discussed in Section 4.1.2 have been included in the Arc Hydro geodatabase, but were not incorporated into the Arc Hydro Framework). Table 4.1 describes the data used in the Arc Hydro Framework for the Llano Basin.

Hydrologic Feature Type	Arc Hydro Feature Class Name	Data Source	Data Generation Process
Stream	HydroEdge	National Hydrography Dataset USGS 1:100,000 scale	Map digitization
Waterbody	Waterbody	National Hydrograpy Dataset USGS 1:100,000 scale	Map digitization
Watershed	Watershed	CRWR/Halff HMS Watersheds from 30 meter DEM's	Raster processing
Monitoring point	MonitoringPoint	LCRA Hydromet GIS shapefile	LCRA survey

Table 4.1: Source data for the Llano River Arc Hydro Framework

Step 2. Data Preparation

Considerable data preparation was required so that the GIS data could be effectively loaded into the Arc Hydro Framework. First, data was organized and condensed into single files for each of the feature types listed in the table above. The National Hydrography Dataset (NHD) is divided into separate files for different hydrologic regions known as Hydrologic Unit Codes (HUCs). There are three HUCs in the Llano River basin, and so these files were merged together using ArcGIS tools. It was also important to select an appropriate projection for the data. Albers Equal Area was used for this project since it accurately maintains the areas of polygon features. The details of this projection and the relevant geographic coordinate system are included below:

Projection: Albers
Parameters:
  False_Easting: 1000000.000000
  False_Northing: 1000000.000000
  Central_Meridian: -100.000000

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Standard_Parallel_1: 27.416667
Standard_Parallel_2: 34.916667
Latitude_Of_Origin: 31.166667

Linear Unit: Meter (1.000000)

Geographic Coordinate System:
Name: GCS_North_American_1983
Angular Unit: Degree (0.017453292519943295)
Prime Meridian: Greenwich (0.000000000000000000)
Datum: D_North_American_1983
  Spheroid: GRS_1980
    Semimajor Axis: 6378137.000000000000000000
    Semiminor Axis: 6356752.314140356100000000
    Inverse Flattening: 298.257222101000020000

Data also needed to be corrected wherever it did not accurately reflect the hydrologic reality of the basin under consideration. For this project, the most common errors were missing stream segments, causing certain sections of the NHD river network to be unconnected.

Step 3. Creating the Arc Hydro Geodatabase

As discussed in Chapter 2, all Arc Hydro vector and time series data are stored in a geodatabase. The name of the geodatabase is left to the user's discretion; for the Llano project, it was simply named "ArcHydro". Inside the geodatabase is a series of classes, and the most common type of class is a "feature class". Feature classes store the spatial (vector) data for the project, and they may be organized into "feature datasets". Feature datasets store a common spatial reference frame for a series of feature classes with related themes.   In addition to feature classes and datasets, the geodatabase may also include relationship classes, networks, and tables, which will be discussed in more detail later in this report. The first data to be loaded into the Llano River geodatabase were the feature classes listed in Table 4.1. Other elements of the Arc Hydro Framework are added in

later steps. Figure 4.4 shows an example of the completed Arc Hydro Framework geodatabase structure.
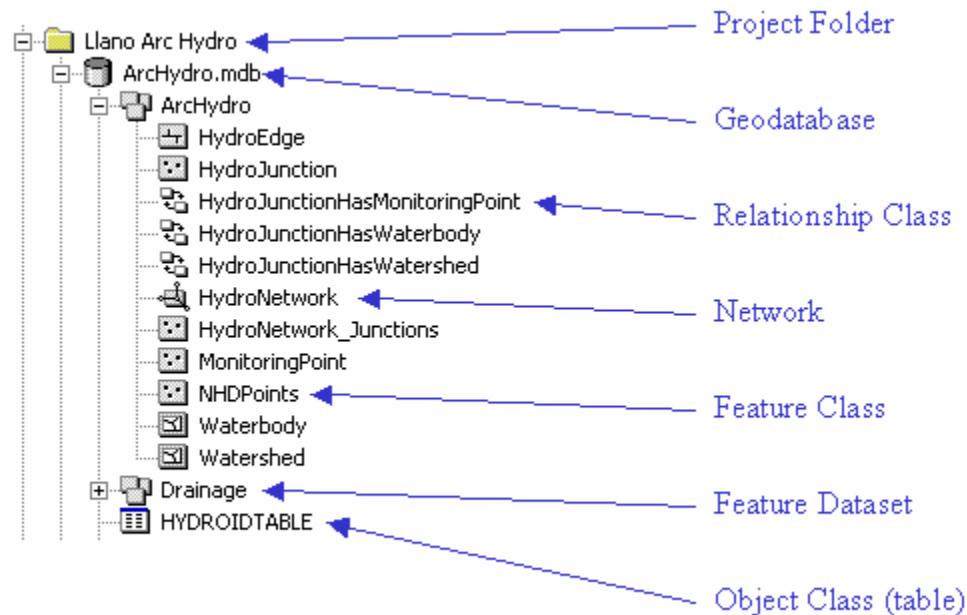
Figure 4.4 – The geodatabase structure

Step 4. Creating HydroJunctions

HydroJunctions are used to mark all points of interest along the stream network (HydroEdge feature class). In the case of the Arc Hydro Framework model, HydroJunctions are used to mark waterbody outlets, watershed outlets, and stream monitoring locations. They can be created in a number of ways, but some methods are more efficient than others. For this project, MonitoringPoint features were copied into the HydroJunction feature class and snapped to the nearest HydroEdge. Once created, HydroJunctions were related to their associated feature classes (watersheds, waterbodies, and monitoring points) through relationship classes. The Figure 4.5 shows monitoring

points (located at their surveyed location) and their associated HydroJunctions (located exactly on the stream network) for Llano River basin.
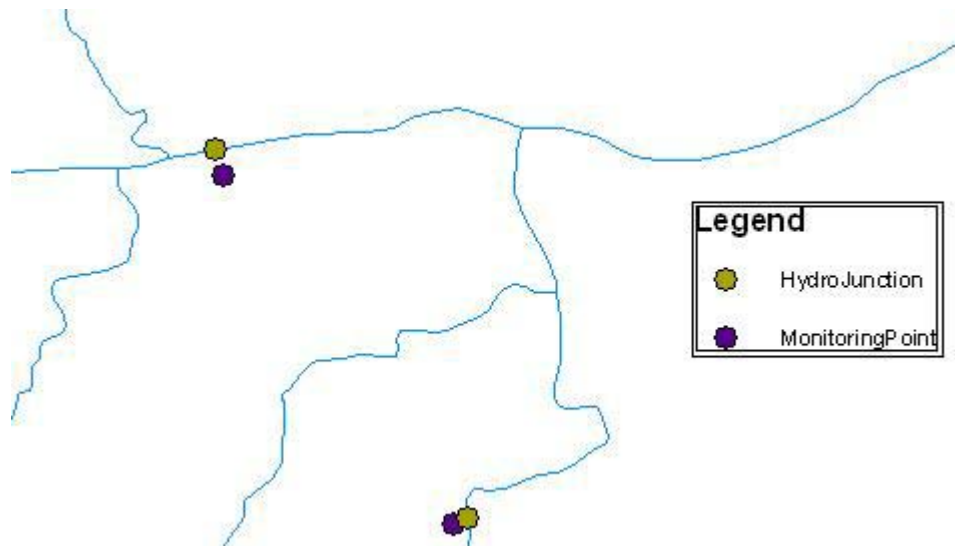
Figure 4.5 – HydroJunctions and MonitoringPoints

Step 5. Creating the HydroNetwork

Once the HydroEdge and HydroJunction feature classes were built, the creation of a HydroNetwork involved two main steps. The first was the creation of a geometric network within ArcCatalog. This was a simple process, but all HydroEdges had to be connected, and all HydroJunctions had to lie directly on HydroEdges for it to function properly. The second step was to set correct flow direction for each HydroEdge in the geometric network. This was not a tedious process, and only a minimal amount of manual editing was required to set these directions. The tutorial includes the details of the methods used to set flow directions. Figure 4.6 shows properly assigned flow directions for a section of the Llano River.
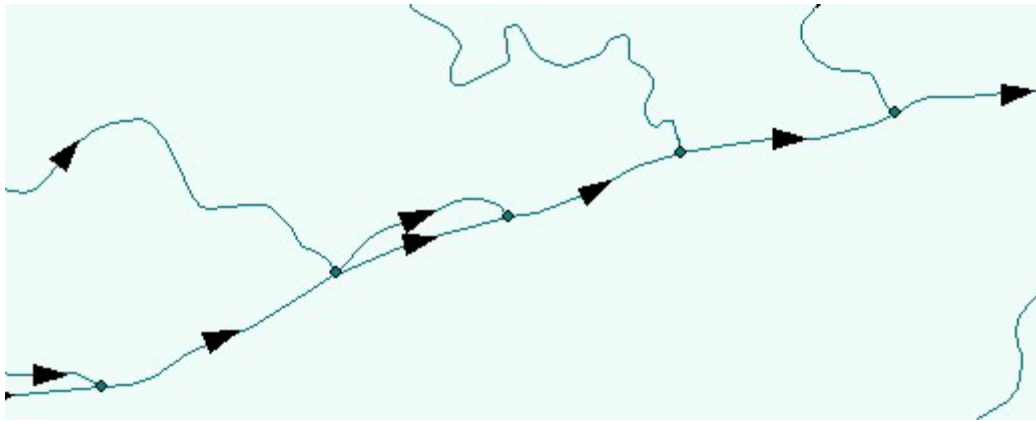
Figure 4.6 – HydroEdges with properly assigned flow directions

Step 6. Implementing the ArcHydro Schema

As discussed in Chapter 2, the Arc Hydro data model is a standardized database format for hydrologic elements. By this phase in the Arc Hydro development process, many of these standardized elements (feature classes and fields) had already been created. Nonetheless, many other elements still had to be added. This was accomplished by applying an Arc Hydro Schema (in this case the "Arc Hydro Framework with Time Series" schema). The schema automatically checks to see what classes and fields already exist, and then creates empty classes and fields for whatever elements do not yet exist. These empty fields and classes were filled by methods detailed in the tutorial, as discussed in Step 7.

Step 7. Assigning Arc Hydro Attribute Values

As mentioned in Step 6, the schema created many empty fields within the various feature classes. Some of these fields are necessary in order for the schema relationships to be complete. Other fields are simply informational, such as attribute fields containing the areas of the watersheds or the distances HydroJunctions are located from the basin

outlet. The Arc Hydro toolset provides methods for filling many of these fields. These methods are described in the tutorial.

Step 8. Finishing

Upon completion, it was necessary to "clean up" the geodatabase. Any fields and feature classes that were not required by Arc Hydro and the LCRA were removed. Table 4.2 shows the feature classes and fields used in the completed Arc Hydro Framework data model.

Field	Description	Populated by
HydroEdge Feature Class		
Enabled	part of network: yes/no	ArcGIS/ArcHydro tools
HydroID	numeric identifier for feature	ArcGIS/ArcHydro tools
HydroCode	text identifier for feature	NHD COM_ID
ReachCode	text identifier for reach	NHD RCH_COM_ID
Name	geographic name	NHD common name
LengthKm	length of edge	ArcGIS/ArcHydro tools
LengthDown	length to basin outlet	ArcGIS/ArcHydro tools
FlowDir	flow direction	ArcGIS/ArcHydro tools
Ftype	type of HydroEdge	NHD FTYPE
EdgeType	type: flowline/shoreline	ArcGIS/ArcHydro tools
HydroJunction Feature Class		
AncillaryRole	type of network junction	ArcGIS/ArcHydro tools
Enabled	part of network: yes/no	ArcGIS/ArcHydro tools
HydroID	numeric identifier for feature	ArcGIS/ArcHydro tools
HydroCode	text identifier for feature	(empty)
NextDownID	HydroID for next Junction	ArcGIS/ArcHydro tools
LengthDown	length to basin outlet	ArcGIS/ArcHydro tools
DrainArea	total area draining to point	ArcGIS/ArcHydro tools
Ftype	type of HydroJunction	ArcGIS/ArcHydro tools
MonitoringPoint Feature Class		
HydroID	numeric identifier for feature	ArcGIS/ArcHydro tools
JunctionID	related HydroJunction H.ID	ArcGIS/ArcHydro tools
HydroCode	text identifier for feature	LCRA Site ID
Ftype	type of monitoring point	LCRA Gage Type
Name	geographic name	LCRA Location N
LONG_DD	longitude of site	LCRA LONG_DD
LAT_DD	latitude of site	LCRA LAT_DD
X_COORD	state plane horizontal	LCRA X_COORD
Y_COORD	state plane vertical	LCRA Y_COORD

Table 4.2: Feature classes in the LCRA Arc Hydro Framework

(continued on following page)

Field	Description	Populated by
Waterbody Feature Class		
HydroID	numeric identifier for feature	ArcGIS/ArcHydro tools
JunctionID	related HydroJunction H.ID	ArcGIS/ArcHydro tools
HydroCode	text identifier for feature	NHD COM_ID
Ftype	type of waterbody	NHD FTYPE
Name	geographic name	NHD common name
AreaSqKm	area in squre kilometers	ArcGIS/ArcHydro tools
Watershed Feature Class		
HydroID	numeric identifier for feature	ArcGIS/ArcHydro tools
JunctionID	related HydroJunction H.ID	ArcGIS/ArcHydro tools
HydroCode	text identifier for feature	HEC-HMS subbasin name
DrainID	related drainage area H.ID	(empty)
NextDownID	HydroID for next Watershed	ArcGIS/ArcHydro tools
AreaSqKm	area in squre kilometers	ArcGIS/ArcHydro tools

Table 4.2: Feature classes in the LCRA Arc Hydro Framework (continued)

HydroID Options

HydroID's are assigned to every feature in the Arc Hydro data model except HydroNetwork_Junctions. The HydroID serves as a unique identifier for each feature and is necessary for establishing Arc Hydro's feature relationships. The allowable range of HydroID values is from 1 to 2,000,000,000. For this project, HydroID's were assigned as a normal counting series (1,2,3,4…) up to a value of about 2,500. This assignment scheme was very generic, and worked well for this project because of its limited scope. However, for larger projects, the user may wish to assign certain ranges of HydroID's to certain features. For instance, HydroEdges might be assigned a HydroID range of 1,000,0000 to 1,999,999 and HydroJunctions a range of 2,000,000 to 2,999,999. Another option is to assign HydroID's based on location. An example of this would be assigning a unique range of HydroID's to each tributary area in the Lower Colorado River Basin

(Llano Basin, Pedernales Basin, etc.). Assigning different areas different ranges of HydroID's allows those areas be easily selected, and to be maintained in separate geodatabases.

4.1.4 Arc Hydro Time Series Development

Once the Arc Hydro Framework has been completed, features such as HydroEdges and MonitoringPoints can be related to timeseries data. Water quality, flow, lake level, and precipitation are all examples of time-varying data that are can be related to specific spatial features. These data are also the primary input and output of many hydrologic, hydraulic, water management, and water quality models. Because of the apparent value of such data, a time series component was included in the Arc Hydro data model. This section discusses how that component was utilized for this project.

Source Data

The primary source for time series data was the LCRA's Hydromet database. As discussed in Chapter 3, this database stores the data collected from a number of gaging stations, located throughout the Lower Colorado River Basin. Of primary interest to this project were stage, flow, and precipitation records for the Llano River Basin. As a test case, approximately eleven years of these data (Nov. 1991 - Dec. 2002) were extracted from the Hydromet in the form of flat files. The time interval for this dataset was one hour.

A second source of time series data was the gridded radar data developed by the NEXRAIN Corporation. NEXRAIN data is collected in 15-minute intervals over a two-kilometer square grid. As discussed in Chapter 3, the gridded rainfall is typically lumped onto CFS watersheds, and sent to the LCRA in this form (the LCRA does not typically receive the gridded version of this data). The LCRA and CRWR have requested samples

of the gridded rainfall, though, and the data has been provided in the form of flat files (tab or comma delimited). For this project, there were two gridded NEXRAIN datasets to work with. The first of these covered 10 days in October of 1998. The coverage area for this dataset was the Lower Colorado River Basin (pink area in Figure 4.7). The second dataset covered the entire month of September, 2003, over a large square region of central Texas (blue area in Figure 4.7). Figure 4.8 shows example NEXRAIN flat file. Note that time varies horizontally across the file and location varies vertically. A value is recorded for every time-location combination, although most values are zero.
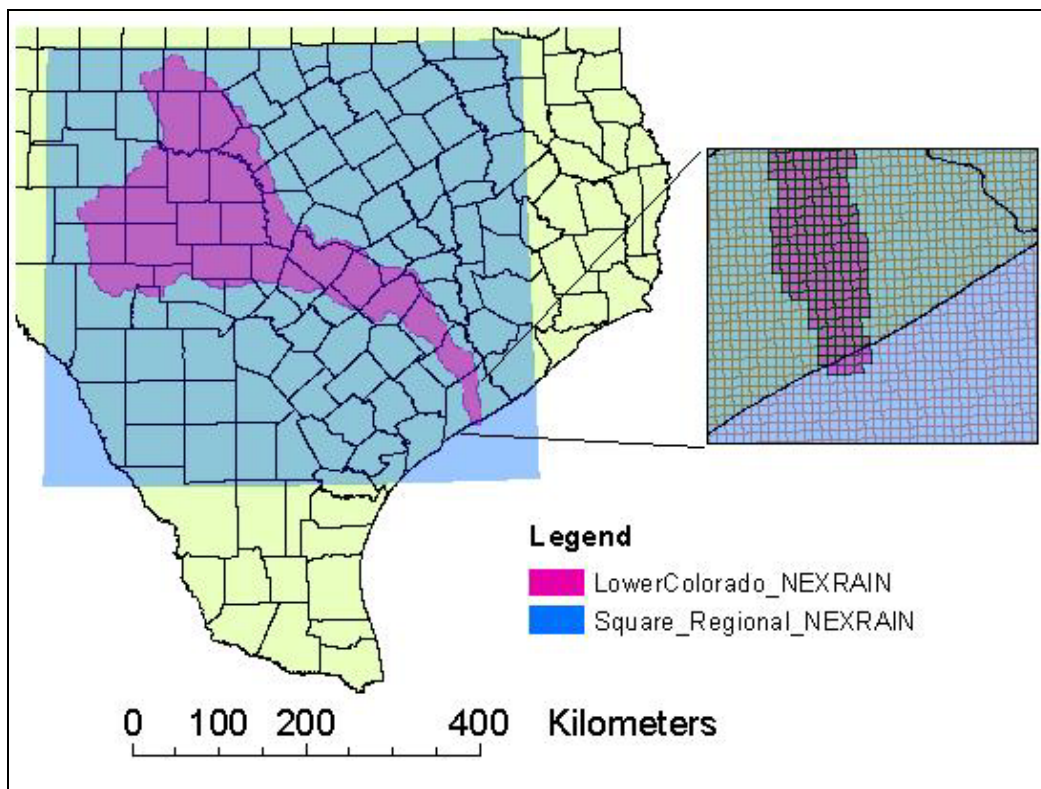
Figure 4.7 – Two NEXRAIN coverage areas

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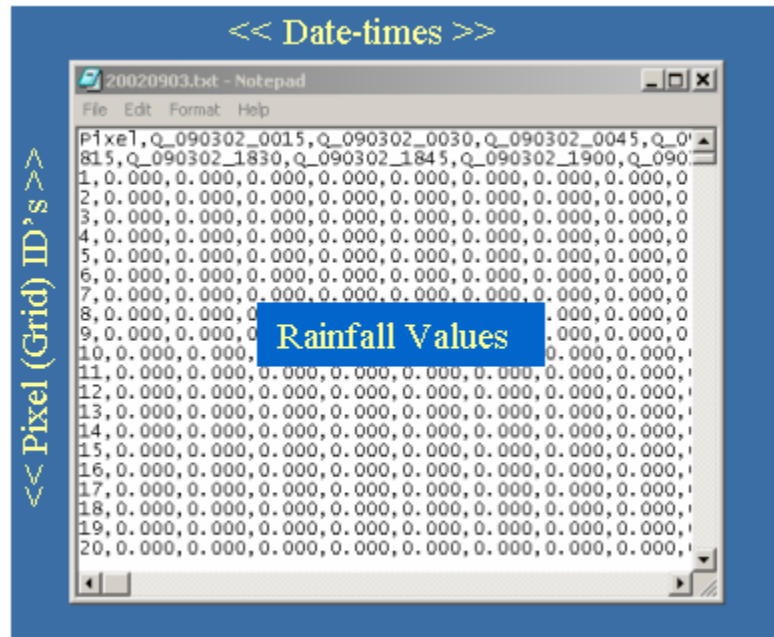
Figure 4.8 – NEXRAIN flat file for September 3, 2002

Conversion to the Arc Hydro Format

The Hydromet and NEXRAIN data were converted to the standard Arc Hydro time series format. This format consists of two tables, a TSType table and a TimeSeries table. The TSType table stores metadata for the different time series types, including the variable measured, the units of measurement, how the data were generated, and other descriptors. The TimeSeries table stores the actual time series values, as well as the location of where the time series takes place, the date-time of the measurement, and the TSTypeID – which relates to the TSType table. Figure 4.9 shows example TimeSeries and TSType tables that were created for LCRA Hydromet data. These time series data are related to Hydromet gages (MonitoringPoint features).

Conversion of the Hydromet data was a relatively simple process because the Hydromet and Arc Hydro time series formats are quite similar. For both formats,

generally, every time series value is assigned to a unique record (although, the Hydromet can sometimes store two directly related values in the same record – i.e. stage and flow). Conversion of NEXRAIN data was somewhat more complicated because the NEXRAIN flat file format, shown in Figure 4.8, is very unlike the Arc Hydro time series format. A Visual Basic program developed at CRWR was used to accomplish this conversion. The Arc Hydro format proved to be an efficient method for storing NEXRAIN data because all records with a TSValue of zero could be omitted. Because of this, the amount of disk space saved by using the Arc Hydro format instead of the flat file format varied depending upon the number of non-zero rainfall values. For typical NEXRAIN data that includes some rainfall but no major storm events, the Arc Hydro format could result in a 97% reduction in the required disk space.

TSType Table

OBJECTID*	TSTypeID*	Variable	Units	IsRegular	TSInterval	DataType	Origin
3	1	Flow	cfs	True	1Hour	Inst-Value	Recorded
4	11	Stage	feet	True	1Hour	Inst-Value	Recorded
5	0	Precip	in	True	1Hour	Step-Cumulative	Recorded

TimeSeries Table

OBJECTID*	TSDateTime	TSValue	TSTypeID*	FeatureID*
1	10/8/2002 4:00:00 PM	5.39	11	14
2	10/8/2002 5:00:00 PM	5.36	11	14
3	10/8/2002 6:00:00 PM	5.37	11	14
4	10/8/2002 7:00:00 PM	5.35	11	14
5	10/8/2002 8:00:00 PM	5.36	11	14
6	10/8/2002 9:00:00 PM	5.35	11	14
7	10/8/2002 10:00:00 PM	5.36	11	14
8	10/8/2002 11:00:00 PM	5.37	11	14

Figure 4.9 – Example TSType and TimeSeries tables

Time Series Evaluation Procedure

To evaluate the effectiveness of the Arc Hydro time series format, goals for time series usability had to be established. These goals were based on the demands a typical GIS analyst is likely to put on a time series dataset. A set of time series functionality goals is listed below.

1. The ability to select from the TimeSeries table based on querying the table's fields (i.e. TSValue > 5)

2. The ability to query the TimeSeries table through the Arc Hydro relationship classes. (i.e. select the time series values related to a given MonitoringPoint)

3. The ability to load and delete data from the TimeSeries table.

4. The ability to map the data over various spatial datasets (time series animations).

Various time series data sets were tested against these four goals. Limitations in performance were discovered under some scenarios. These results are discussed in further detail in Chapter 5.

4.1.5 Arc Hydro for Microsoft SQL Server

Up to this point, the Arc Hydro data model has only been considered in terms of the personal database (.mdb), and indeed, the personal database is the most common GIS storage container. The use of personal databases has many advantages. First of all, personal databases may be easily copied and distributed between different users. Second, these geodatabases may be edited using Microsoft Access, with which many users are very familiar. Third, their relatively simple structure, availability, and ease of use means that a staff of highly trained database technicians is not required.

There are, however, two problems with personal databases. First, only one user can access a personal database at a time. This means that separate copies of a database must be created for each user. With several copies of a database in existence, it is difficult to keep track of which contains the most recent and most accurate set of data. A second problem with personal databases is that they are not an efficient way to store large quantities of data. In fact, a personal geodatabase cannot be larger than two gigabytes.

A relational (or multi-user) database, such as Microsoft SQL Server, is the answer to the limitations of personal databases. In general, a relational database can be accessed by a number of independent users through a network system. Also, relational databases can handle datasets of almost unlimited size; which can be particularly beneficial when dealing with large time series data sets. For these reasons, a goal of this project was to establish the Arc Hydro data model on the LCRA's "Hyperion" SQL Server.

Implementing the Arc Hydro Framework in SQL Server

The key to storing GIS data within a relational database is ESRI's ArcSDE (Spatial Data Engine). ArcSDE sets up a series of tables within the relational database in

order to maintain GIS-specific data and functions. According to ESRI, ArcSDE accomplishes the following tasks (ESRI website, 2003):

1. Provides the infrastructure required to manage multiple users editing the same spatial database with long transactions, alternate versions, and history.

2. Provides the business logic software for not only creating simple geometric data, but also technology for supporting advanced GIS data types such as images, networks, features with integrated topology and shared geometry, and associating these with rules, behavior and other object properties.

3. Allows GIS data to be directly maintained in the format of "spatial types" supported by the DBMS vendors (building on their parallel efforts to develop spatial extensions).

4. Integrates the spatial (geometric) search capability provided by the DBMS vendors within the ArcGIS client software applications.

The primary challenge to working with ArcSDE was the initial setup of the SQL Server. Only directly through the server can geodatabases and users be created. Users must be created with appropriate permission levels that allow or block them from viewing, editing, and creating new tables and feature classes. Someone with expertise in servers and ArcSDE is generally required to complete this initial setup. For this reason, the GIS database specialists at the LCRA provided essential assistance to CRWR during this part of the research project.

Once a geodatabase and user permission levels were established on the SQL Server, the Arc Hydro Framework data for the Llano River basin were successfully transferred into that geodatabase. This was accomplished through a fairly simple process. First, the Llano Basin Arc Hydro Framework was built in a personal geodatabase (see Chapter 7). Second, the Arc Hydro Framework schema was applied to an empty SQL

Server geodatabase. Third, using ArcCatalog and ArcMap, data were loaded from the completed personal geodatabase into the empty SQL Server geodatabase. The resulting ArcCatalog structure is shown in Figure 4.10. Note the elaborate naming conventions for SDE database connections and feature classes.

Although Arc Hydro data have been successfully loaded onto the LCRA's SQL Server, there are a few administrative questions that must be answered before such data can be used organization-wide. One question concerns how user permission levels will be assigned. The lowest permission level allows the user to view, but not edit the data. A higher level of permission allows the user to edit existing tables (or feature classes) within the geodatabase. The highest level allows the user create new tables, as well as edit existing ones.
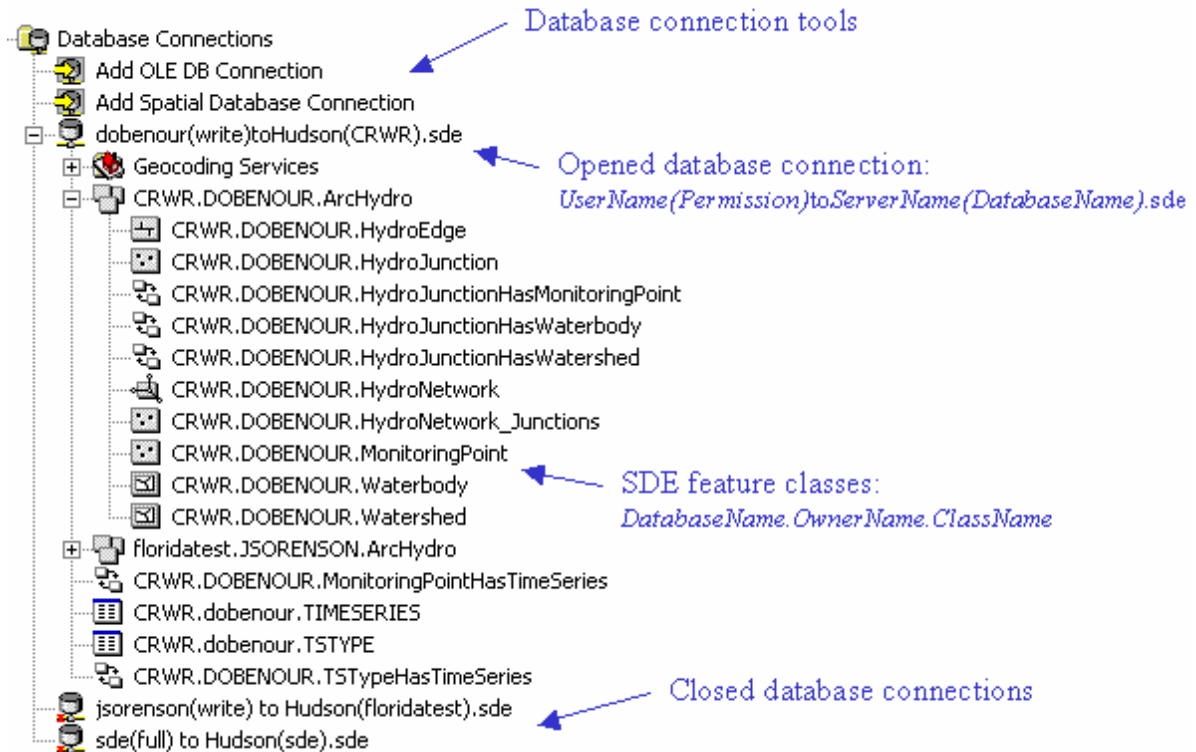
Figure 4.10 – An ArcCatalog view of GIS data on SQL Server

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Another issue involves the question of versioning. Versioning allows multiple users to concurrently edit a geodatabase. Each editor is assigned their own "version" of the geodatabase. Each editor's version records all of the edits that he or she has made to the geodatabase. Eventually, however, in order to make these edits permanent, the edits must be incorporated back into the over-all geodatabase (this is termed "compressing"). This raises the question of how often versions should be compressed back into the geodatabase, and also, what procedure should be taken if different versions are found to have conflicting edits.

4.2 CREATING AN INTERFACE DATA MODEL (IDM)

4.2.1 IDM Theory

The term "hydrologic modeling" is meant to include all types of computational, water-related modeling efforts including hydraulic, hydrology, water resources, and water quality analysis. Using GIS to aid in hydrologic modeling is not a new concept. The research team at CRWR has pursued this goal for many years. In fact, the Arc Hydro data model is one important step toward reaching this goal. The concept of connecting Arc Hydro to a hydrologic model to form a "hydrologic information system" was illustrated in Figure 1.1.

To many, Figure 1.1 implies that the Arc Hydro data model can be used as the primary data storage system for hydrologic modeling. However, this is only partially true. Arc Hydro was not designed to store many of the parameters required by hydrologic models (i.e. curve number, time of concentration, etc.). It is possible to expand the Arc Hydro data model to store these parameters, but this is only practical for simple models. For more complex hydrologic models, like HEC-HMS, Arc Hydro is not an effective method of storing model parameters.

For more complex hydrologic models, an Interface Data Model (IDM) may be the most efficient way to store hydrologic model data within GIS. An IDM is designed to store the parameters and data required for a specific hydrologic modeling program, including both input and output time series data. In addition to this, the goals of an IDM are as follows:

1. Provide a database capable of storing all model data, so that the data may be queried and retrieved efficiently.

2. Store data in a manner so that they are readily transferable between the geodatabase format and the format required by the computational model.

3. Store the model's spatial data in a manner that can be easily viewed in ArcMap.

4. Store data in a format compatible with the Arc Hydro naming conventions.

5. Provide a link between the IDM spatial data and the associated Arc Hydro spatial data, thus providing a connection between the IDM and Arc Hydro geodatabases.

6. Provide a data storage structure that is intuitive to the user.

7. Minimize the size of the geodatabase (in terms of disk space).

With an IDM, the conceptual image of a hydrologic information system changes, as shown in Figure 4.11. The most important link is between the IDM and the hydrologic model. This link is responsible for the flow of input and output data, as well as the modification of model parameters. The link between the IDM and Arc Hydro is not always necessary, but it is advantageous from a data management standpoint. At CRWR, the Arc Hydro data model is used to coordinate data transfer between different hydrologic models, making the IDM-Arc Hydro link essential for managing data connectivity within GIS (Robayo, 2004). The link between the IDM and Arc Hydro is also important if model results are to be translated back into the Arc Hydro format, for use with time series viewing tools.
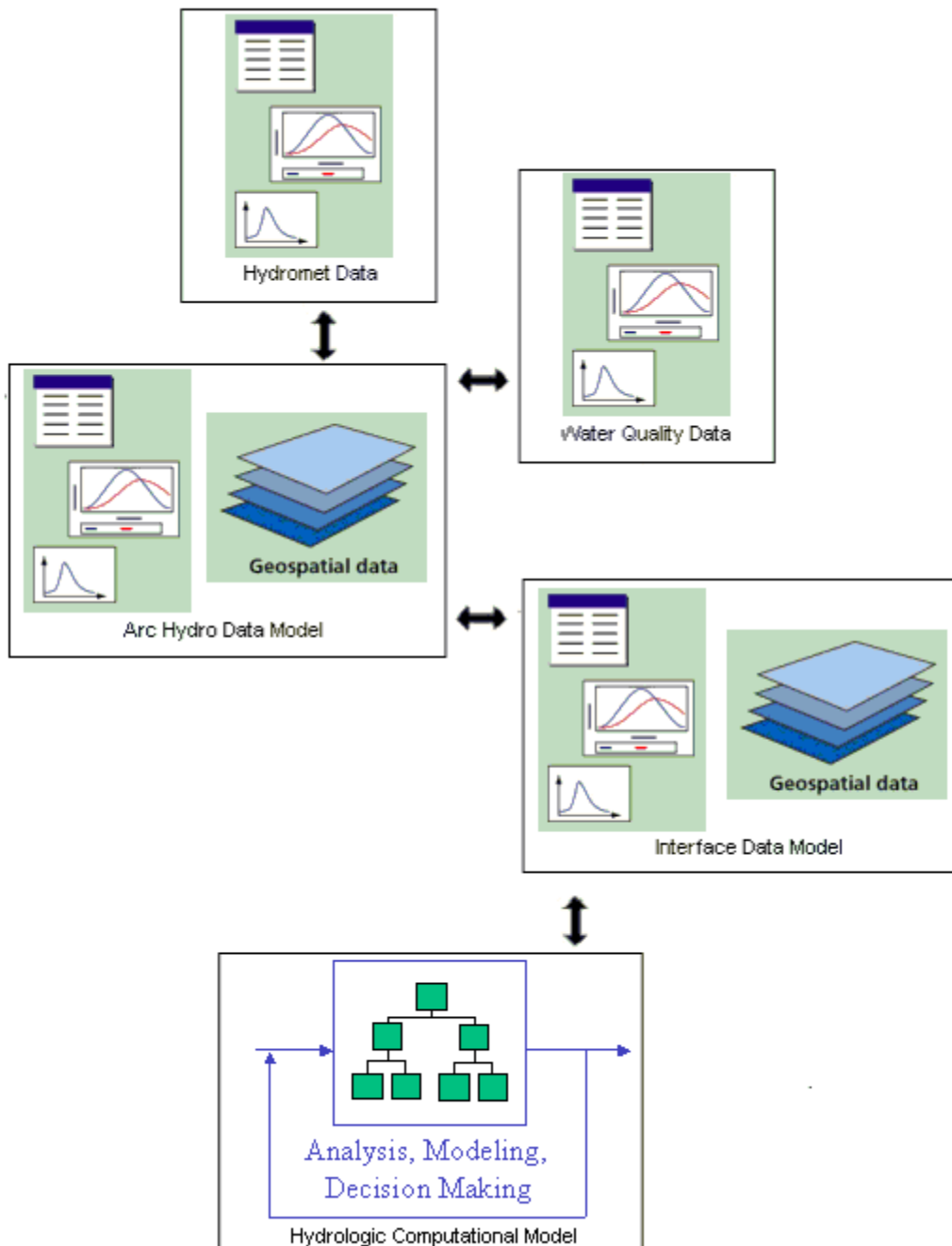
Figure 4.11 – IDM and hydrologic modeling for the LCRA (adapted from Maidment, 2002)

4.2.2 Introduction to Data Model Design

UML Design

Most data models are the result of an intensive design process. GIS data models are typically created using the Unified Modeling Language (UML). UML is an intuitive method of design that does not involve coding, but rather the creation of database diagrams. These diagrams must be created in specialized programs, such as Visio, so that they may be transformed into actual database formats (repositories) when finished.

Reading a UML diagram can be difficult at first. Understanding the terminology used in these diagrams is the key thing. It is important to note that many of the terms have overlapping definitions. For instance, a feature class is a type of object class. A list of UML/GIS terminology follows below:

1. Class – A database entity, such as a table.
2. Object – A record in a table.
3. Attribute – A field in a table.
4. Feature – A record with spatial data; a "GIS object".
5. Object Class – A table of records, typically used when referring to a table without spatial data.
6. Feature Class – An object class with spatial data.
7. Abstract Class – Only appears in UML. It stores a list of fields that apply to all tables inheriting from it.

For an example, consider the UML diagram in Figure 4.12. This UML would create a geodatabase with two feature classes: HMSReach and HMSSubbasin. As shown in the diagram, the HMSReach is a polyline feature class and the HMSSubbasin is a polygon feature class. Also listed inside the feature class elements are attributes (table fields) specific to the individual feature classes. For instance, all HMSSubbasins have an

"Area" attribute, meaning that there is an "Area" field in the HMSSubbasin table. As shown, HMSReach features do not have an "Area" attribute. Immediately above the two feature classes is an abstract class, *HMSFeature*. This class will not actually exist within the database, but all of the attributes listed in it are inherited by both the HMSSubbasin and HMSReach feature class. Therefore, both HMSSubbasin and HMSReach will have a "FeatureID" field. Above *HMSFeature* is another abstract class, simply named *Feature*. This abstract class is ESRI-specific, and it assigns a "shape" field to all classes inheriting from it. Without *Feature,* HMSReach and HMSSubbasin would not be feature classes, instead they would just be regular object classes.
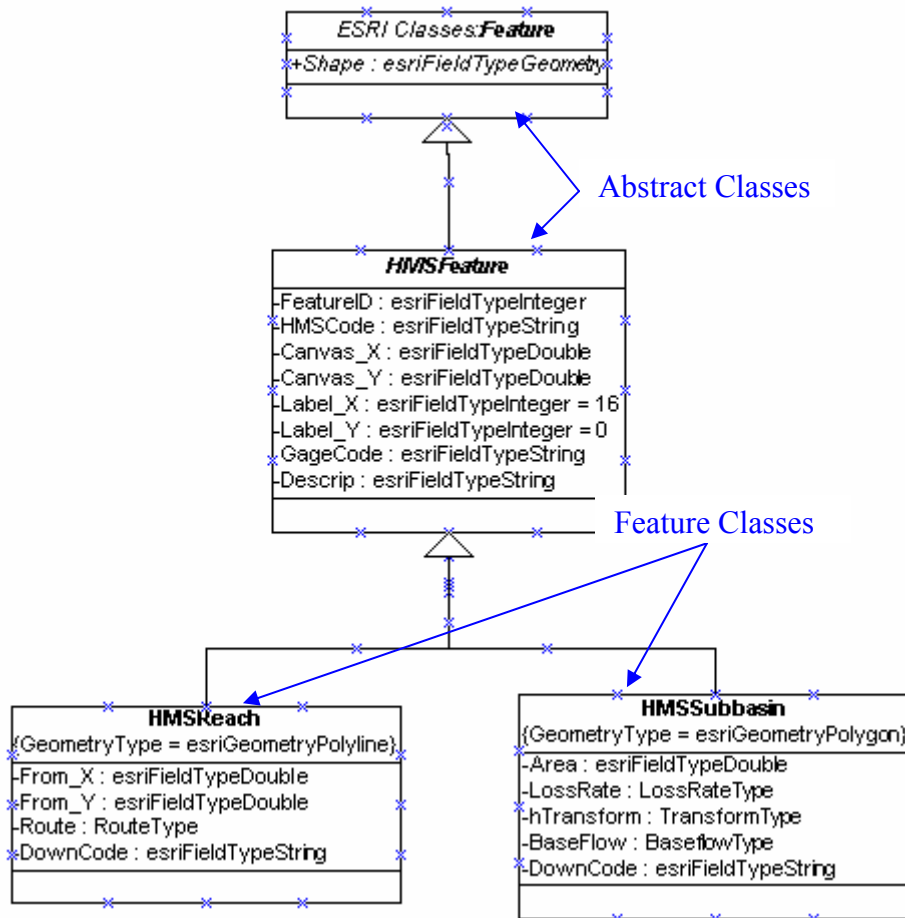
Figure 4.12 – Example UML diagram (taken from the HMS IDM)

Converting the UML Diagram to a Geodatabase

When the UML diagram is finished, it is exported as a database repository. Using the schema generation process in ArcCatalog (see Section 4.1.3, Step 6), the repository may be applied to any geodatabase. In this way, the geodatabase will receive all of the feature classes, object classes, relationships, etc. that were included in the UML diagram. The HMS IDM, as well as the original Arc Hydro data model, were created in this fashion.

4.2.3 An IDM for HEC-HMS

The ArcGIS Interface Data Model for HEC-HMS (HMS IDM) has a very complex design, but this is not unexpected since HEC-HMS is a very complex program. Fortunately, the research team at CRWR has considerable experience with database design, and their assistance proved very valuable. The HEC also took considerable interest in this project, and assisted by providing program documentation, and codes and instructions for dealing with DSS data. A large diagram of the IDM is included in Appendix F.

One purpose of creating the HMS IDM was to prove that the components of a hydrologic model could be effectively translated into a geodatabase format. An "effective" IDM is one that accomplishes the list of goals outlined in Section 4.2.1. (It was not within the scope of this project, however, to create a new software product that is capable of building new HMS models.) Another goal of the IDM was to provide a system for archiving the LCRA's existing HMS model data. For this reason, codes were written to transfer this data from the LCRA's HMS models into the IDM. These codes were only developed for HMS routines used by the LCRA; other data transfer codes still must be developed. A conceptual view of how data are translated back and forth between HMS files and the current IDM design is shown in the Figure 4.13.

The remainder of this section will discuss the details and rational behind the IDM development process. First, the design of the IDM database structure is presented. Second, scenario management inside the IDM is discussed. Finally, the process of transferring data from an existing HMS project to the IDM is presented.
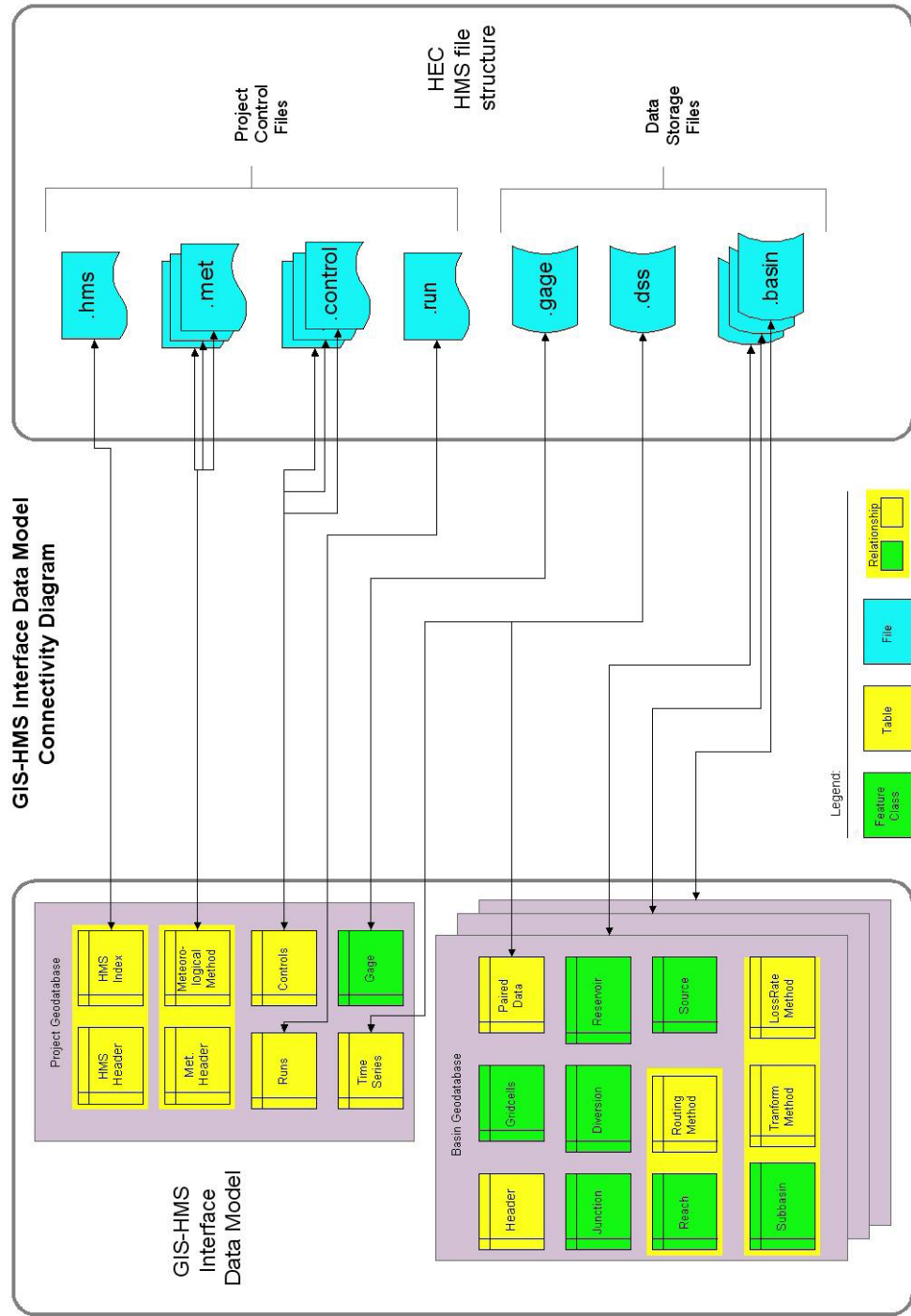
Figure 4.13 – HMS/IDM data connectivity

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4.2.4 IDM Database Structure

As discussed in Chapter 12, a HMS project is made up of a number of unique file types. These files store time series, watershed parameters, and model controls. During the IDM design process, each file type was examined individually in order to determine how it could best be translated to geodatabase format. The first file to be examined was the basin file.

IDM Basin File Components

Except for perhaps DSS files, basin files are typically the largest and most complex files found in a HMS project. They store the structure of the hydrologic network as well as all parameters used for base flow, initial loss, transform, and routing calculations. Inside each basin file, data are arranged in blocks, as shown in the Figure 4.14. Each line in a block includes a description followed by a value, separated by a colon.

It was decided that each geographic entity (junction, reach, etc.) should be represented as a record in a feature class. It was also decided that each description (text preceding the colon in Figure 4.14) in the basin file should become a field name in the IDM. Originally, it was desirable to use the HMS descriptions as field names. However, this was not practical due to the length requirements; field names should have 10 characters or less to ensure compatibility with other database types.   Therefore, descriptions were often reduced, (i.e. "Percent Impervious Area" was reduced to "Impervious").

It was also decided that there would need to be a unique feature class for each basin element (subbasin, junction, reach, etc.) so that each feature would have the correct

geometry type. Subbasins would be represented by a polygon feature class, junctions by a point feature class, reaches by a line feature class, and so on.

```
Junction: JR3200
      Canvas X: 2812178.371                  Junction Block
      Canvas Y: 10242975.166
      Label X: 16
      Label Y: 0
      Downstream: R3200
End:

Subbasin: R1750w1750                          Subbasin Block
      Canvas X: 2808105.675
      Canvas Y: 10246715.316
      Label X: 16
      Label Y: 0
      Area: 1.636000
      Downstream: JR3200

      LossRate: Initial+Constant
      Percent Impervious Area: 1.15
      Initial Loss: 1.22
      Constant Loss Rate: 0.32

      Transform: Snyder
      SnyderTp: 0.54
      SnyderCp: 0.70

      Baseflow: None
End:
```
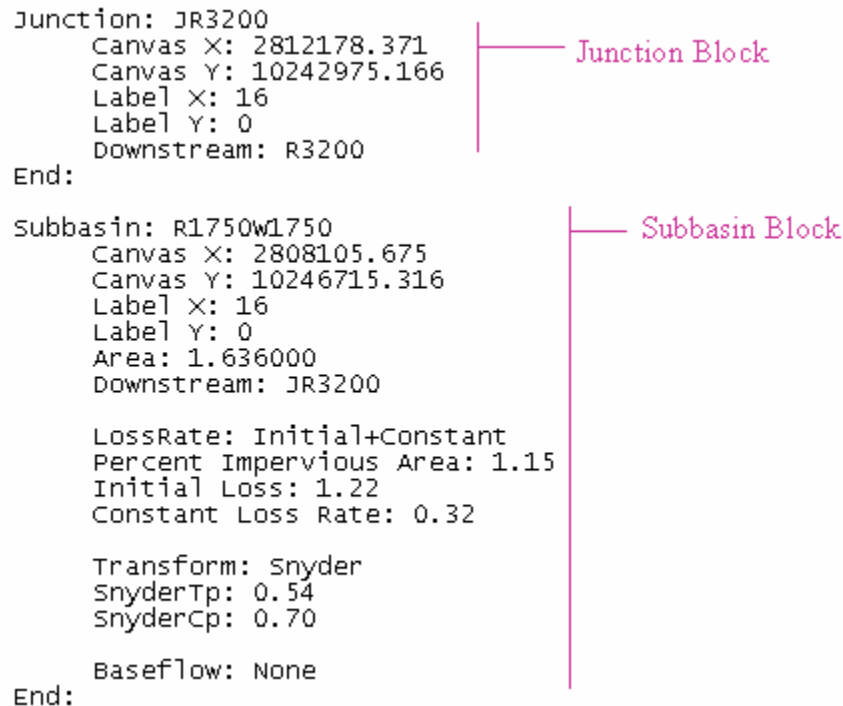
Figure 4.14 – Data blocks from a HMS basin file

In a HMS model, the user may choose from a number of calculation routines for each feature. Every subbasin, for example, has a loss rate routine that calculates the amount of rainwater lost to the subsurface. In the subbasin block of Figure 4.14, there is a section for "LossRate" parameters. This section includes the type of LossRate routine being used ("Initial+Constant") followed by all of the parameters required for the routine. Similarly, there is also a section in the Subbasin block for Transform and Baseflow parameters. It was eventually decided that there should be a separate table (object class) for each routine. In this fashion, routine tables not used by the model can be easily deleted at the user's discretion. Also, a set of relationships was created to associate these

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tables to their corresponding feature class. This system provides an effective structure for data organization and querying within ArcGIS. Figure 4.15 shows an example parameter table.

	OBJECTID*	HMSCode*	Impervious	ILoss	LossRate	BasinCode
	1	R2270W2270	0.11	0.61	0.15	Junction
	2	R3840W2300	0	0.63	0.15	Junction
	3	R2490W2490	0.51	0.84	0.19	Junction
	4	R2480W2480	0.33	0.8	0.04	Junction

Figure 4.15 – Table for Initial+Constant LossRate parameters

IDM Gage File Components

Each HMS project has only one gage file, which stores all of the project's precipitation and discharge gages. They can be used for time series data input (precipitation) or model calibration (stream flow). However, the gage file does not store time series data directly, but instead, the gages are related to time series data stored in DSS files. In the HMS program, gages can be assigned latitude and longitude for calculation purposes, but they cannot be viewed spatially. In the IDM, gages are stored as a point feature class, so that spatial viewing is an option.

IDM Meteorological File Components

HMS meteorological models control how rainfall data is distributed over the HMS basin. For example, a typical meteorological model could associate various HMS rainfall gages with various HMS subbasins. There are other meteorological methods too, and the user must select which method to use for a particular HMS scenario. Meteorological models relate spatial rainfall data to spatial watershed data. Therefore, meteorological methods are analogous to sophisticated relationship classes, and the

meteorological file defines the details of this relationship. Inside the IDM, each meteorological method is represented by a set of tables (one to three tables).

IDM DSS File Components

The HEC's Data Storage System (DSS) provides an effective way of storing time series, paired data, and gridded data. Time series DSS data include input precipitation data, output stream flow data, model calibration data, etc. DSS paired data include, among other items, stream and reservoir routing data. DSS grid cell data generally stores precipitation input data.

DSS stores records in "blocks" (similar to tables). These blocks are referenced by their DSS pathnames, which have six unique parts, listed A through F, separated by forward slashes (/). Each part contains a piece of information (metadata) about the DSS block. Table 4.3 includes a description of each pathname part for the three main types of DSS data. Example pathnames for the Llano HMS project include:

"//R2590/STORAGE-FLOW///LR_MASON/" – for time series

"//R3380W3360/FLOW-DIRECT/01NOV2000/15MIN/LR_JUNCTION/" – for time series

Pathname Part	Time series metadata	Grid Cell metadata	Paired Data metadata HMS Version 2.1	Paired Data metadata HMS Version 2.2
A	(blank)	Grid type	(blank)	(blank)
B	Location	Source/Location	Location	Location & Basin
C	Variable type	Variable type	Variable type	Variable type
D	Start of time block	Interval start time	(blank)	(blank)
E	Time interval	Interval end time	(blank)	(blank)
F	Source	(blank)	Basin	Format

Table 4.3: DSS pathname metadata

In addition to the DSS pathnames, there are additional DSS metadata stored in "DSS headers". Each DSS block can have its own unique header data. Unlike pathname metadata, however, header metadata cannot be easily accessed and queried using HEC software. Unlike the rigid structure of pathnames, the structure of header data is more flexible and varies considerably between the different types of DSS data. Both "pathname" and common "header" metadata are stored in "Catalog" tables in the IDM.

IDM Project Index and Control File Components

In addition to data storage files, a HMS project also has a number of files containing project and scenario management information. These data are not spatial in nature, and fit readily into tables. They are discussed further in Section 4.2.5.

Coded Value Domains

A coded value domain is a list of user-defined values that may be used to populate a field within a database. For example, a field named "sky conditions" might have a coded value domain that includes the possible values: "cloudy", "partly cloudy", and "sunny". Coded value domains were established for fields in the IDM that should only accept certain, HMS-defined values. For example, the LossRate field in the HMSSubbasin feature class stores the type of LossRate calculation the model uses. "Initial+Constant" is an acceptable value, so is "Green and Ampt". However, "InitialPlusConstant" would not be acceptable because it is not recognized by the HMS program. By creating a coded value domain in UML, the user is restricted to selecting from a list of predefined, acceptable values. Figure 4.16 shows how a user selects from a coded value domain.

Figure 4.16 – Coded value domains in ArcMap

IDM Object Identification

In the Arc Hydro data model, features are identified by a "HydroID" and a "HydroCode", which are an integer field and a text field respectively. The HydroID is an arbitrary numeric identifier that is used as a basis for the model's relationships. The HydroCode is a text identifier that gives the feature a name meaningful to the GIS user. In the IDM, basin features are identified by a "HMSCode", which is a text field. HMSCodes are the IDM equivalent of the HydroID and HydroCode together. HMSCodes, therefore, serve a dual purpose. Like HydroID's, HMSCodes are the basis for IDM relationships; like HydroCodes, they provide a naming system that is meaningful to the user. HMSCodes are equivalent to the names given to the elements within the HMS program. For instance, a reach element named "R300" in the HMS project, will translate into a reach feature with HMSCode = "R300" in the IDM.

As discussed previously, Arc Hydro data relationships are based on an integer field named "HydroID". Therefore, in the GIS-HMS IDM, use of an equivalent integer field named "HMSID" was considered. The primary advantage of the "HMSID" was that integer fields may be queried more quickly than text fields, thus improving IDM performance. The disadvantage of using the "HMSID" was that it would require

intensive ID management and maintenance because these values are not maintained by the HMS program. The advantage of "HMSCode" is that it requires little maintenance because the field is simply populated by the names of the HMS elements. In the end, the "HMSID" concept was abandoned because the increase in performance that it allowed was minimal.

HMSCodes are used only for HMS basin elements, but many other HMS elements also have a "code" field. Gage features, for instance, are identified by the attribute "GageCode". Furthermore, there are a series of identification codes used in scenario management. A "RunCode", for example, is the name of a particular HMS project scenario. As with HMSCodes, the values of identification codes in the project geodatabase translate directly into the names of these elements in the HMS project. Table 4.4 gives a description of the code fields in use by the IDM.

Code	Description
HMSCode	Name of an individual HMS basin feature
GageCode	Name of an individual HMS gage
BasinCode	Name of a basin model
MetCode	Name of a meteorological model
ContrlCode	Name of a set of control specifications
RunCode	Name of a project model run (scenario)

Table 4.4: IDM identification codes

In addition to identification codes, all features in the IDM have a "FeatureID" attribute. This attribute is an integer field that has the capability of linking IDM features to Arc Hydro features. The IDM FeatureID field is populated with the HydroID's of equivalent Arc Hydro features. Populating this field is optional, but it is the most effective way to create a link between features in the IDM and the corresponding features in Arc Hydro.

4.2.5 IDM Scenario Management

A HMS project can include multiple basin files, meteorological files and control files. Scenarios, known as HMS "runs", are created by taking different combinations of these three file types. Therefore, a HMS model with two basin files, two meteorological files, and two control files could have a maximum of 8 (2^3) unique runs. In the IDM, the run information is stored in the "Project_Runs" table. Every record in this table represents a unique run and points to a specific basin, meteorological, and control model.

Whether or not to include scenario management tables within the IDM was a major design option. Because scenario management information does not have a spatial component, the advantages of storing it within GIS seemed minimal. Nonetheless, it was eventually decided to include these tables for the following reasons:

1. One of the goals of the IDM is that it be a data archive. This archive would not be complete without the inclusion of scenario management data.

2. All HMS time series results are referenced by the HMS run (scenario) in which they were created. Therefore, scenario information must be maintained so that these time series results may be understood and related within the IDM.

3. A future goal is to run HMS model calculations from within the GIS environment. The scenario management data must be maintained in order to perform these calculations.

IDM Structure for Multiple Basins

As discussed previously, a single HMS project may include an unlimited number of basin files. Each of these basin files includes a number of spatial features (junctions, reaches, etc.). Some of these basin files may represent the same geographic watershed, but with different versions of parameter values. Other basin files may represent entirely different geographic locations.

How to store data for multiple basin files within the same data model was a subject of much debate during the IDM development process. It was at this point in the research that the concept of using more than one geodatabase was first considered. There were three obvious alternatives for how the IDM might store these spatial features:

1. Store all of the basin features in a single feature dataset (in the same geodatabase).

2. Store the features of each basin file in a unique feature dataset (in the same geodatabase).

3. Store the features of each basin file in a unique geodatabase.

The first option, although certainly possible, had one severe disadvantage. Storing the features of multiple basin files within the same feature class, could lead to overlapping features when basin files represent similar geographic areas. Overlapping features in GIS can be very confusing to the user, especially if the features share exactly the same spatial coordinates. This option would also force all DSS time series to be stored in one geodatabase, which may not be desirable based on performance issues. The one advantage of this approach is that it would allow all HMS project data to be stored in a single geodatabase.

The second option proved to be much less feasible than the first. The reason for this is that no two tables in the same geodatabase can have the same name, even if they are in separate feature datasets. Therefore, if this method were employed, standardized

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table names like "HMSJunction" could no longer be used. Furthermore, because standardized table names could not exist, standardized data relationships could not exist. To solve this problem, codes would need to be written to create feature classes with unique names (i.e. HMSJunction1, HMSJunction2, HMSJunction3…). This would be no trivial task and it would greatly complicate the IDM. Therefore, this option was discarded.

The third option was originally thought to be too cumbersome to be practical. It involved the creation of a separate basin geodatabase for every basin file. Eventually, however, it was determined to be the best way to prevent overlapping features, and at the same time, allow standardized table and relationship class names.

It was eventually decided that option #3 would be the most effective way to store multiple basin files. However, a modification was made to allow basin files with identical geographies, but different watershed parameters to be stored in the same geodatabase. In this case, because the features are identical, they would be stored only once in their respective feature classes. Parameter tables, however, would store a unique record for each basin file, which would be recognized by a "BasinCode" attribute. In this manner, multiple calibrations of the same watershed could be stored within the same geodatabase.

IDM Structure for Multiple Meteorological Files

Meteorological models describe how gaged rainfall data are distributed over a watershed. Although the rainfall data are spatial and the watershed data are spatial, the meteorological data are not spatial. Meteorological data are simply a set of instructions that define the relationship between rain gages (or rain grids) and the watershed. Because of this, there are no concerns regarding overlapping features. Therefore, multiple meteorological models can be satisfactorily stored in one set of tables (similar to option

#1 for basin files). Storing each meteorological model in a unique geodatabase is unnecessary.

4.2.6 Linking the IDM with HMS data

To make the IDM functional, there has to be a method for transferring data back and forth between it and the HMS file structure. This has been accomplished to a limited degree by this thesis (and further progress is being made at Texas A&M University). The primary focus, for this project, has been on transferring data from the LCRA's existing HMS models to the IDM. Therefore, codes have been developed for transferring the types of HMS elements that exist within the LCRA's models. In general, codes have been written to import data into the IDM, but not to export them back to HMS.

Visual Basic (VB) was the chosen method for moving data from HMS files to the IDM. VB provides all of the functionality necessary for this task, and it is the program most familiar to the CRWR research team. There has been some discussion of using XML, but based on a discussion with Dean Djokic (personal communication, 2003), XML would only provide an advantage for exporting data from the IDM, not for importing them. In the future, when codes are written to export the data back into HMS files, XML should be further considered. A set of the VB codes are included on CD in the back of this report, and a brief tutorial on how to use them is included in Appendix G.

Transferring HMS Text Files to the IDM

As discussed previously, all HMS files except DSS files are text files. Therefore, the codes developed to transfer these files are basically text parsers. They search the text file for key words, get the value associated with that word, and transfer that value to the appropriate geodatabase location. Separate codes were written for the various types of HMS text files. Figure 4.17 shows the GUI interface for one of these programs.

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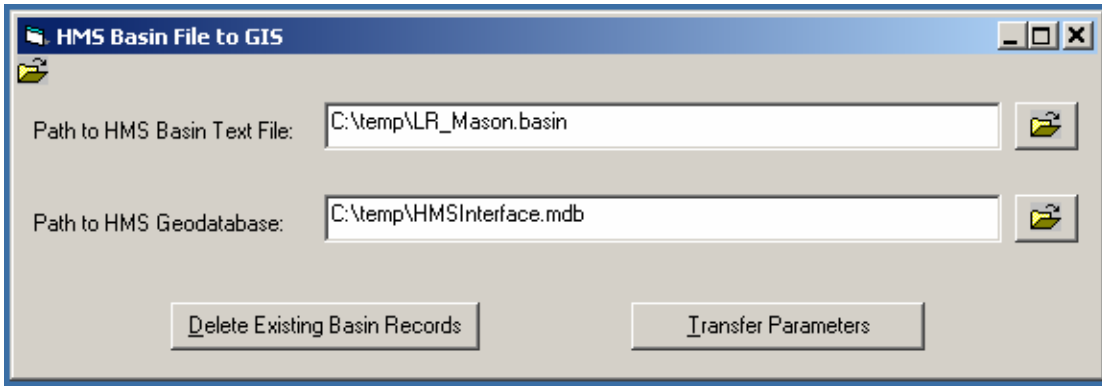
Figure 4.17 – Program for transferring a HMS basin file to the IDM

Transferring Shape Data to the IDM

Shape data must come from a source other than the text files. In the case of the LCRA/Halff HMS models, shape data are available in the form of GIS files created by Halff & Associates. The original data were shapefiles, but they were converted to geodatabase feature classes for this project. Therefore, a code was written to transfer these shape data from a geodatabase made from Halff GIS files to the IDM geodatabases. The GUI for this code is shown in Figure 4.18. Note that shape data are transferred from "source" feature classes to "target" feature classes based on matching attribute values in the "Match Fields".
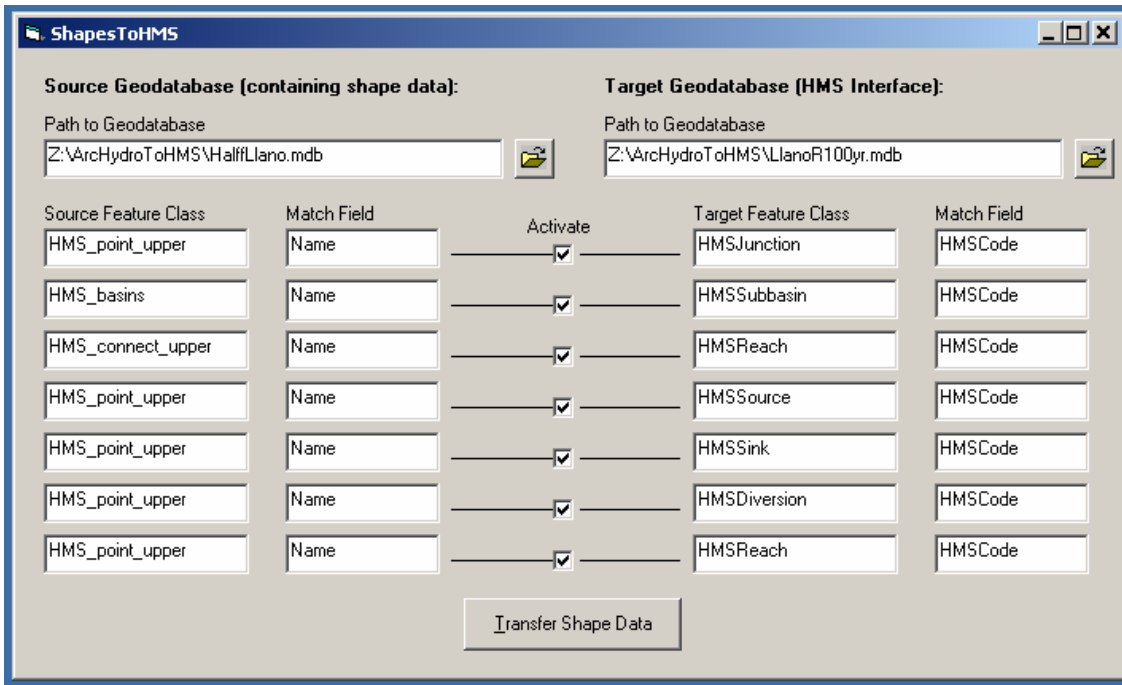
Figure 4.18 – Program for transferring GIS shape data to the IDM

Transferring HMS DSS Files to the IDM and Back

The transfer of DSS data is a slightly more complicated task. To begin with, DSS has a binary storage structure that requires specialized HEC routines in order to manipulate. Therefore, the VB program must call these routines, which are stored in a dynamic link library (the name of the file is "heclib50.dll" and it is typically stored under the "System32" folder in Windows). Another complication involves the sheer size of DSS files. The DSS file (HEC binary format) for the Halff/LCRA historical model of the Llano River Basin is nearly 60 megabytes in size. Therefore, the DSS transfer program was designed to handle these large files as efficiently as possible. Nonetheless, transferring complete DSS files to the IDM can be a time-consuming effort. Unlike for the other data types, programs were written to transfer time series data in both directions: IDM to HMS, as well as HMS to IDM. As shown in Figure 4.19, data from a DSS file

may be selected for importation to the IDM based on a query of the A through F parts of the DSS pathname.
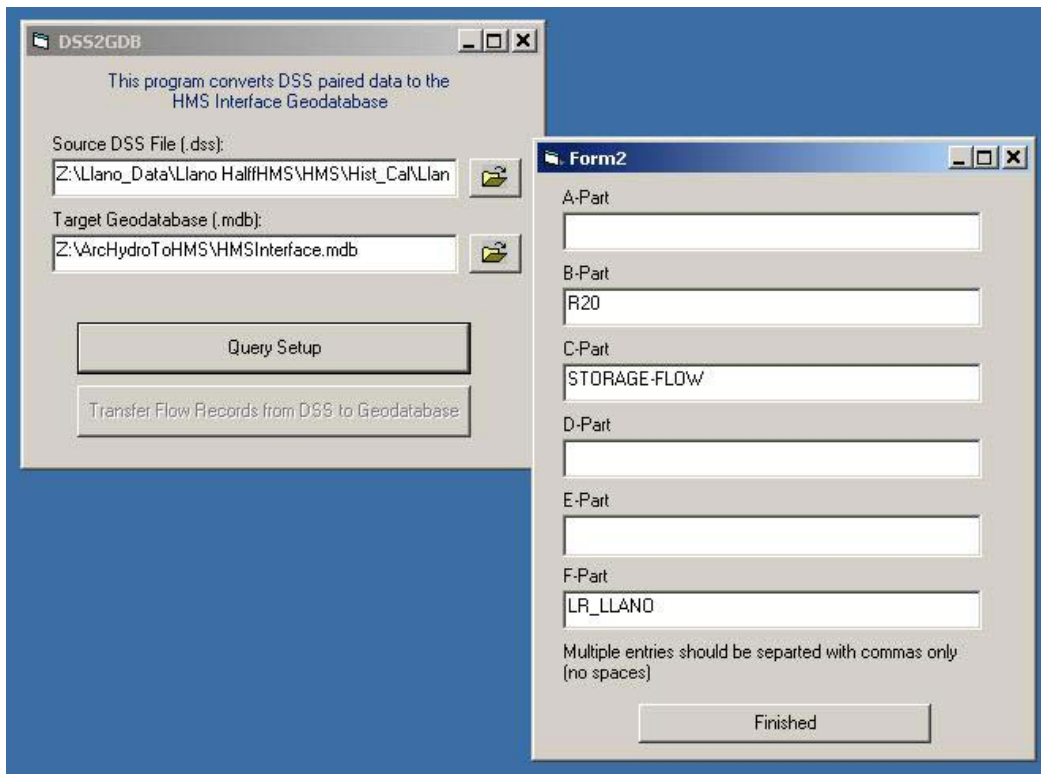
Figure 4.19 – Program for transferring DSS paired data to the IDM

Once completed, these tools were used to populate a prototype IDM with data from one of the LCRA's existing HEC-HMS models. For this purpose, the tools proved very satisfactory. The populated model that resulted is discussed in Chapter 5.

4.3 CREATING A GIS-BASED FLOOD DAMAGE EVALUATION SYSTEM

This section discusses how GIS and the concepts developed by this report can be applied to performing water resources calculations. In this case, the application is for flood mapping and the determination of flood damages. This section of the report is divided into three main parts. First, the objectives of this work will be discussed. Second, the flood map generation process will be presented, followed by the flood damage assessment process. Next, a data model developed specifically for this work will be discussed. Finally, the development of an ArcGIS Model Builder process, designed to automate these calculations, will be presented.

4.3.1 System Objectives

Flood Maps

Flood maps are developed primarily as a visual aid for flood analysis. The resolution of these maps vary depending upon the needs of the user and the quality of the input data. To develop high-resolution flood maps, the user must possess sufficiently detailed terrain elevation data, and sufficiently accurate and robust hydraulic models. Based on discussions with Melinda Luna, an LCRA engineer specializing in river hydraulics, uncertainty in the hydraulic model is generally more of a limiting factor than the availability of quality terrain data (personal communication, 2004).

The LCRA currently has no standardized routine for developing floodplain maps. When maps are generated, HEC-GeoRAS is usually the method of choice. However, HEC-GeoRAS has been found to have a number of limitations that greatly reduce the quality and/or speed of map generation. These limitations include problems caused by river sinuosity and river coves, which are discussed in greater detail in the next section.

In many cases, the results of HEC-GeoRAS require many hours of hand editing to produce a map of sufficient quality.

As a result of the Halff/LCRA H&H study discussed in Chapter 3, the LCRA now posses a set of "official" floodplain maps for various return-frequency storms (2-year, 5-year, etc.) as shown in Figure 4.20. These flood maps were calculated using extremely detailed terrain TINs (around 300 megabytes each) that were too large to be used with HEC-GeoRAS. To work around this problem, Halff and Associates developed a custom program to intersect the water surface TINs with the very-detailed terrain TINs. According to Erin Atkinson of Halff and Associates, this program would take around 12 hours to execute (personal communication, 2004).
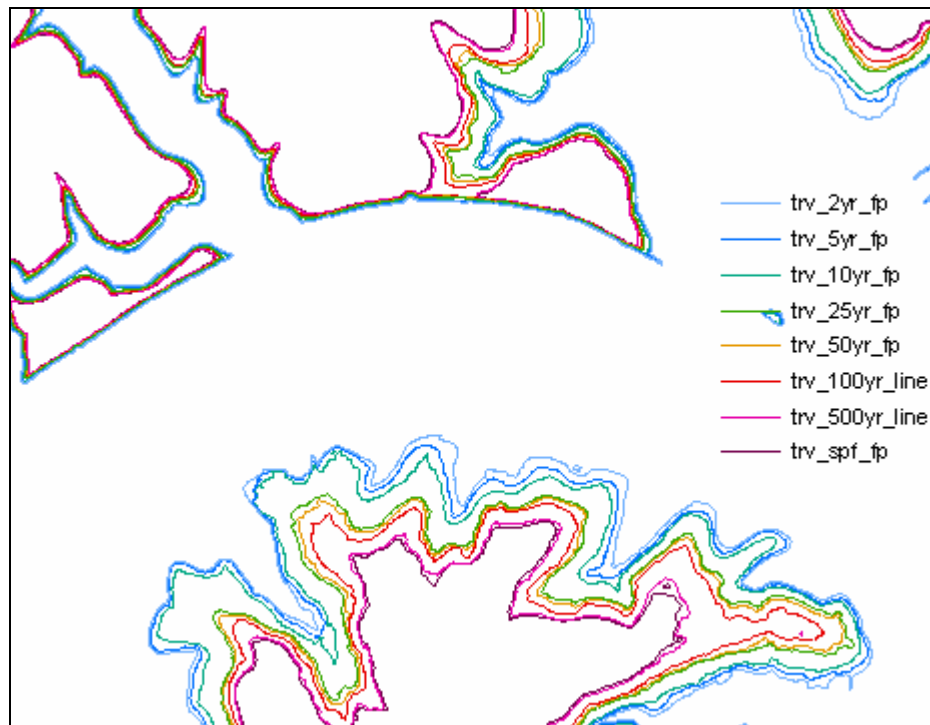
Figure 4.20 – LCRA/Halff flood shapefiles for return-frequency storms (Lake Travis)

The goal of this research effort is to develop a procedure for generating floodplain maps at a much faster rate, so that flood map generation could potentially become a part of the real-time flood forecasting system. These maps would be used primarily as a visual aid, and are not necessarily intended for use in further calculations. Nonetheless, a goal is to make these maps comparable in quality to the maps generated by Halff and Associates.

Damage Reports

The LCRA does not calculate flood damage reports on a regular basis. As with floodplain maps, however, they do have detailed damage assessments for the various return-frequency storms. These damage reports were generated using the HEC's Flood Damage Assessment (FDA) procedure discussed in Chapter 2.

There were two primary goals for the damage report procedures developed by this research. First, these reports need to be generated quickly so that, like floodplain maps, they could become part of real-time flood analysis. Second, it was desired that these calculations be performed on a spatially distributed basis, for the reasons discussed in Chapter 2.

The damage report system developed by this research currently returns only the number of structures inundated and the depth of inundation for each structure. The damage report system does not currently provide the economic value of these damages. However, assuming that economic data is available for the various floodplain structures, then calculating total economic damage would be a straightforward extension of the procedure presented here.

Results Archive

It was also determined that there needs to be a procedure for archiving the results generated by this flood evaluation process. Therefore, a data model was developed to facilitate calculations and to store results. The Arc Hydro data model was considered, but due to the nature of the results data, Arc Hydro was determined not be an appropriate repository. Arc Hydro generally stores permanent watershed information; not temporary and arbitrary model results.

4.3.2 Flood Map Generation

The flood map generation process is well established, relatively simple, and well documented by programs such as HEC-GeoRAS. In general, flood maps are created by comparing the calculated water surface elevation to the land surface elevation continuously across the floodplain. Where the water surface elevation is greater than the land surface elevation, inundation occurs. The remainder of this section focuses on areas where the standard method of floodplain generation had to be modified to meet the unique needs of the LCRA.

Land Surface Representation

As discussed in the previous section, the terrain TINs used by the Halff study are too large to be used in real-time flood forecasting operations. Therefore, it was decided that these TINs must be converted into a more useable format. One option was to try to decrease the resolution of the TINs. However, there is no method for accomplishing this using standard ArcGIS tools, and it was eventually decided that TIN modification was not a useful approach in this research.

The other option was to convert the TINs to rasters (grids) of reasonable resolution. It was decided that a 20-foot cell size would be appropriate since this is

comparable to the size of most floodplain structures, as shown in Figure 4.21. This resulted in rasters of approximately 30 megabytes in size – an order of magnitude smaller than their associated TINs.
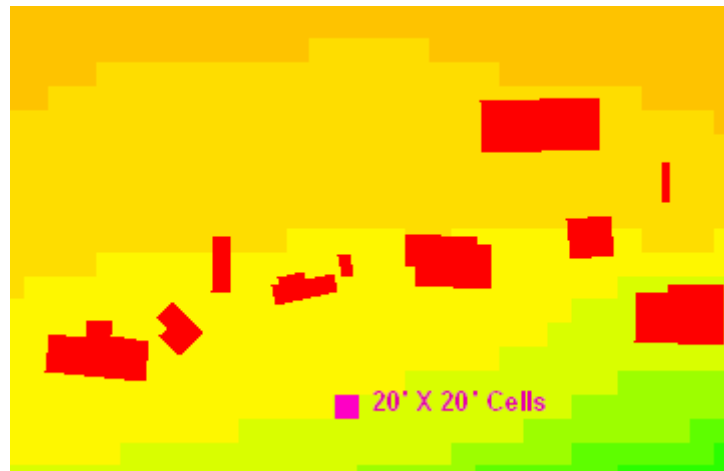
Figure 4.21 – Floodplain structures over a 20-foot raster

The LCRA/Halff H&H study includes twenty original TINs, which cover the entire floodplain of the main stem of the Lower Colorado River Basin. Through the remainder of this report, these twenty TINs will be referred to as "LCRA DEM regions", where DEM stands for digital elevation model. For this project, five of these TINs were converted to rasters, and some of them were merged together. It was assumed that the LCRA will be responsible for converting and merging the remaining TINs.

Water Surface Generation

Water surface elevations are generally represented by a TIN, formed from cross section lines with calculated water surface elevations. The cross sections used for TIN generation are typically the same cross sections used by the hydraulic model. Despite the fact that this method of TIN generation is well established, it does have some potential limitations. The two major limitations were insufficient cross section widths and errors

resulting from river sinuosity. A tutorial that provides detailed instructions for dealing with these limitations is included in the Appendix H.

(A) Insufficient cross section width.

Sometimes the hydraulic cross sections may not be wide enough to span the entire region that needs to be mapped. This is especially true when there are large coves in the river system that extend far beyond the main river channel, as shown in Figure 4.22. In the past, manual editing has been used to extend the inundation polygon into these coves.
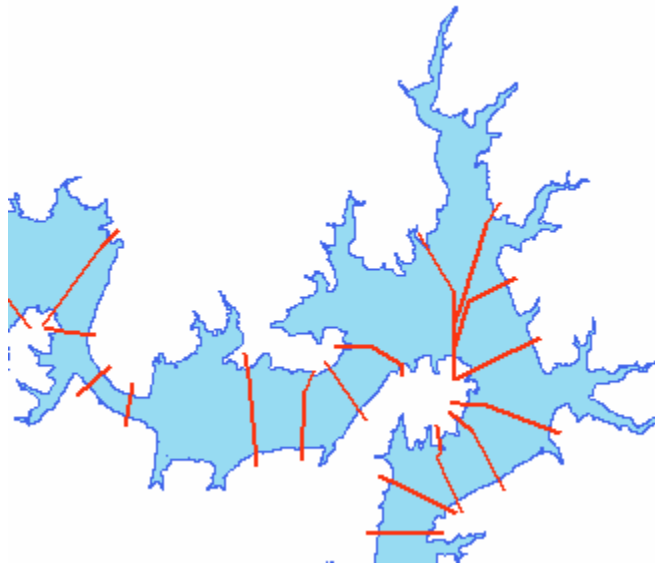
Figure 4.22 – Coves extending beyond hydraulic cross sections on Lake Travis

Two options were considered for solving this problem. The first option, termed the "fill sinks" option and illustrated in Figure 4.23, was to generate a water surface based on the existing hydraulic cross sections. This water surface would be converted into a grid and then merged with the land elevation grid based on the maximum value of the two grids. The resulting raster has pits wherever coves exist outside of the main channel. Using the Arc Hydro "fill sinks" command, the elevation in these coves is then raised to the lowest adjacent water surface elevation (so that all water can "flow" to the

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basin outlet). The resulting "fill grid" represents the land/water surface that exists during flooding. The land surface grid is then subtracted from the "fill grid" to determine flood depths and the resulting floodplain.
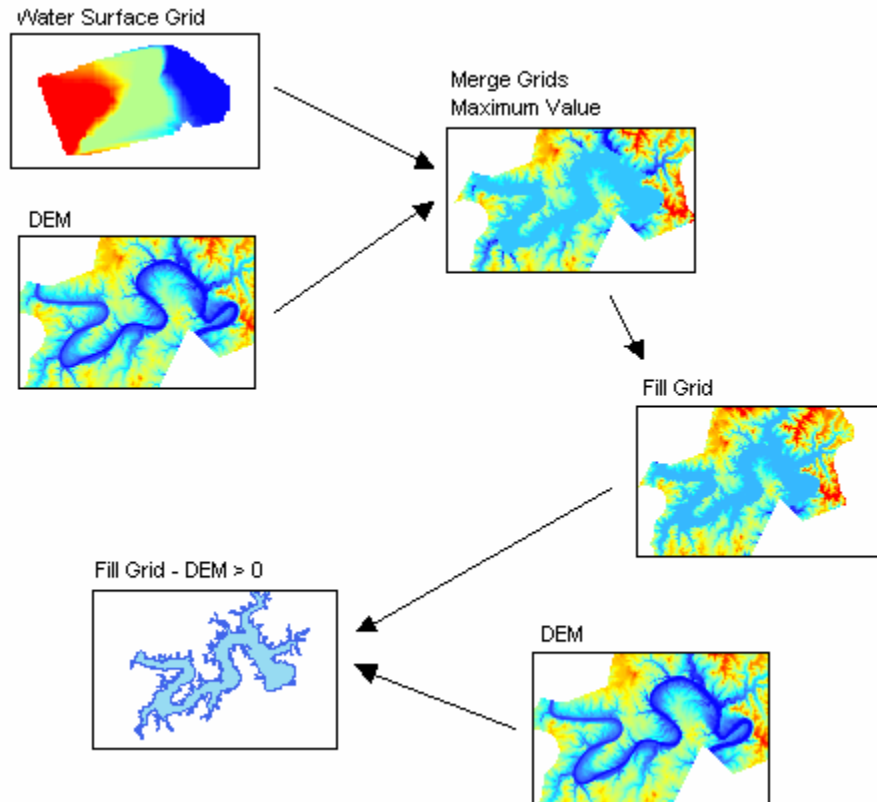
Figure 4.23 – The "fill sinks" solution to mapping cove inundation

The primary advantage of the "fill sinks" method is that it requires no alteration of existing GIS data. It does, however, have some considerable drawbacks. First, the fill sinks command takes approximately 15 minutes to run for a typical LCRA DEM region. Second, this method assigns the lowest adjacent water surface elevation (most downstream elevation) to the coves, and this may not be desirable in areas with steep water surface slopes.

The second method was the manipulation of the hydraulic cross sections to adequately cover the area of inundation. This method, illustrated in Figure 4.24, requires the extension of existing cross sections, and occasionally the addition of new cross sections around large cove features. The only disadvantage of this method is that it requires a considerable initial time investment in order to manually edit the cross sections. The advantages of this method are very considerable, however, because this method does not result in any extra processing time during the flood map generation process. Also, this method gives the user more control over the elevation assigned to the water surface in coves. For these reasons, this was the method used by this research project.
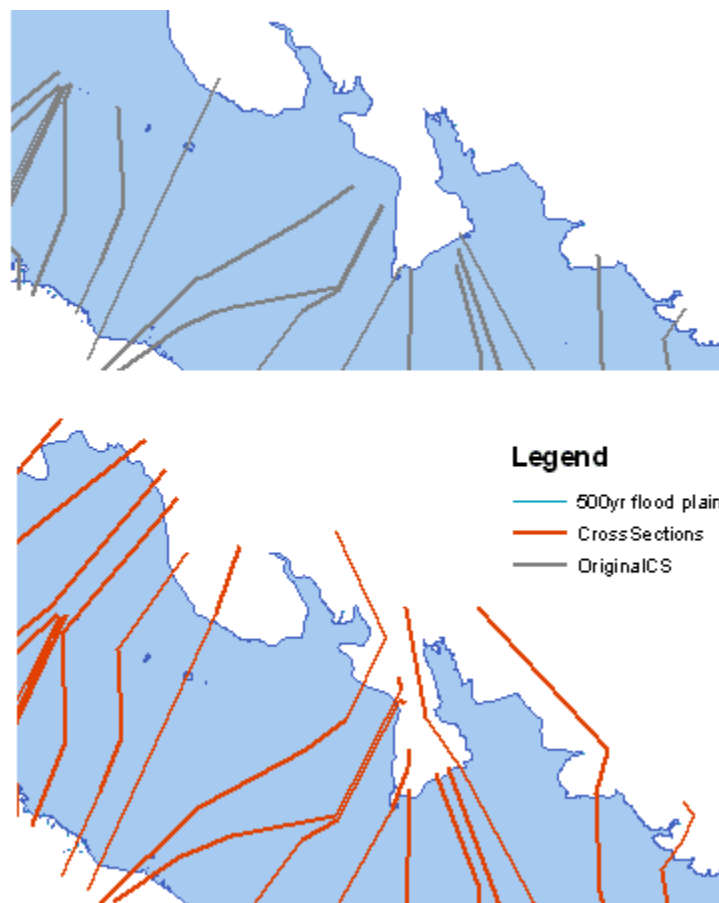
Figure 4.24 – Original cross sections (top) and modified cross sections (bottom)

(B) Errors caused by river sinuosity

River sinuosity refers to the degree that a river's centerline winds and bends along its path. Lake Travis, shown in Figure 4.25, is one of the extremely sinuous regions in the lower Colorado River System. HEC-RAS is a one-dimensional model, and so these bends are largely ignored. However, for floodplain mapping, these bends must be considered, and they can potentially cause inaccuracies when generating the water surface TINs.
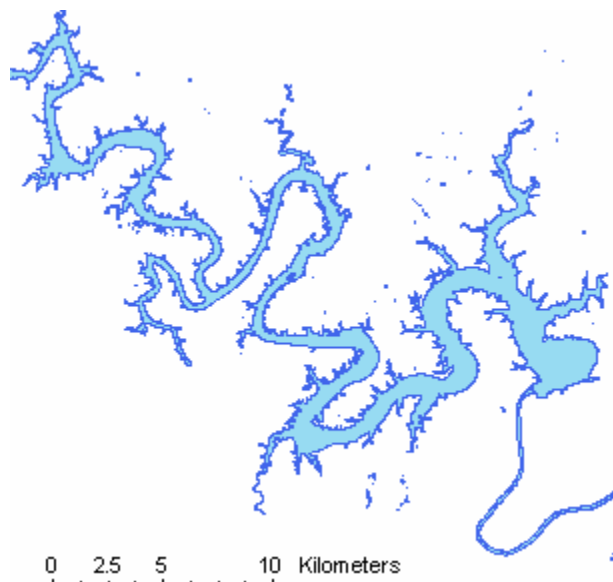
Figure 4.25 – Lake Travis, a particularly sinuous stretch of the Lower Colorado River

In areas where the river has a high level of sinuosity, cross sections located on one side of a sinuous bend may have an impact on the water surface elevations on the other side of the bend. An example of this is illustrated in the top half of Figure 4.3.7. As shown in this figure, the water surface elevations on one side of the river bend are influenced by cross sections on the other side of the bend.

To remedy this problem, a series of minor modifications were tested on the cross sections. It was eventually decided that the most effective manipulation was to toe the cross sections along the inside of the river bend. These toes, shown in the bottom-left of Figure 4.26, are small approximately 90 degree bends the ends of cross sections. In general, these toes could be almost infinitely small, except where the cross sections on the opposite side of the river were more closely spaced (more dense). These toes forced a break in the water surface TIN between one side of the bend and the other, as shown in the bottom-right of Figure 4.26.

TIN Generation from Standard Cross Sections
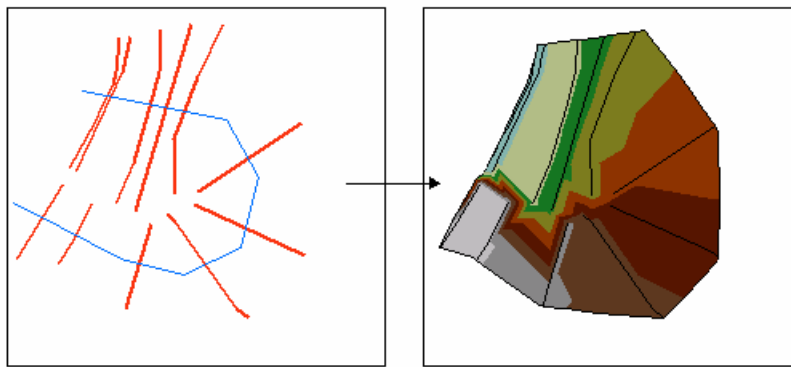
TIN Generation from Modified (toed) Cross Sections
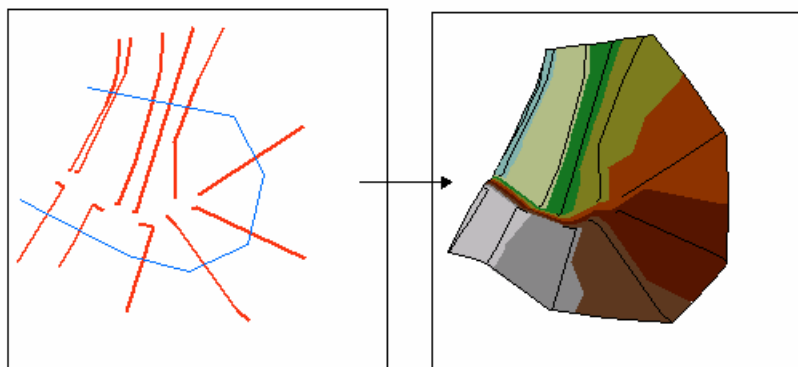
Figure 4.26 – Toeing cross sections to prevent errors caused by river sinuosity

It was also decided that cross sections converging on the inside of a bend could create an unrealistic water surface profile. As shown in the top of Figure 4.27, these cross sections could create an unnatural "wall of water" (area of high water surface slope). For this reason, the cross sections were clipped and spread to create a more natural water surface profile.
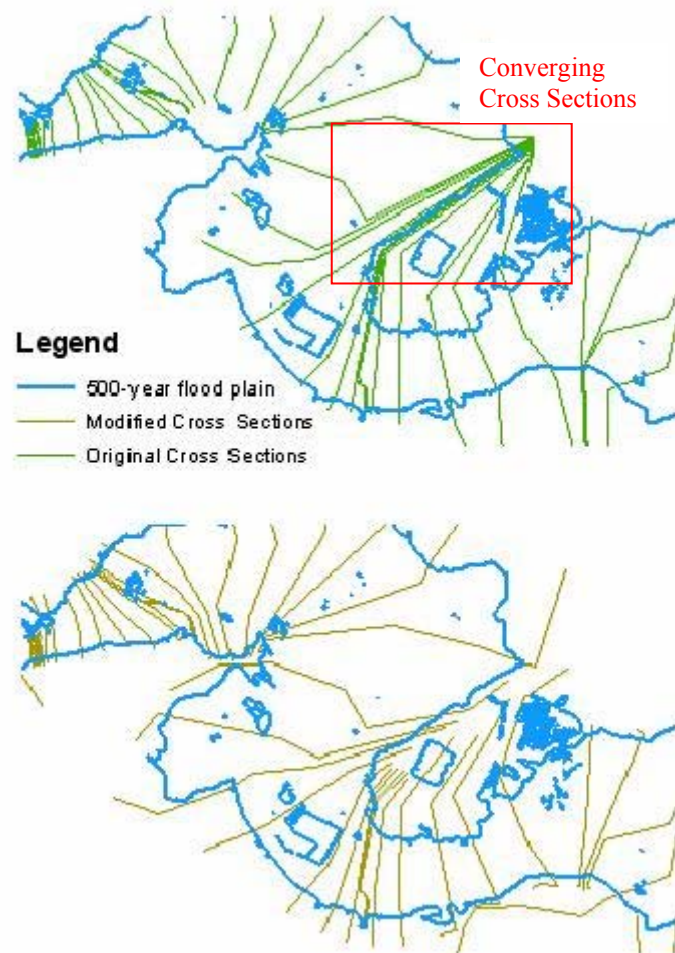
Figure 4.27 – Clipping cross sections on the inside of a river bend

Other methods were also tested to correct the river sinuosity problem. One of these methods was the placement of hard break lines down the center of the bend

(between the cross section ends), which would be used in TIN generation. Another method was to create the TIN with a clip, so that the center of the bend would be a data void. However, neither of these methods produced satisfactory results.

Generating a Floodplain Polygon

Once the cross sections have been satisfactorily modified using the procedure outlined above (and detailed in the report's appendix), these sections and the land surface DEM can be used to create a floodplain polygon. This procedure is straightforward and can be accomplished using tools found in the ArcGIS 2-D (Spatial) and 3-D Analyst Extensions. A summary of this process is listed below:

1. Convert cross sections to a water surface TIN
2. Convert water surface TIN to a raster
3. Subtract land surface raster from water surface raster
4. Create new raster from all cells that have a positive value (Grid Value > 0)
5. Convert new raster to a polygon feature class
6. Dissolve polygons into one record (if desired)

4.3.3 Damage Report Generation

Unlike flood map generation, there were no established procedures for generating flood damage reports on a structure-by-structure basis. Despite this, developing such a procedure was not found to be a particularly difficult endeavor. Virtually all of the tools required to calculate structure inundation depths can be found in ArcMap and the 3-D Analyst Extension. It should be noted that the floodplain map plays no role in the creation of a damage report, the two processes are completely independent.

As shown in Figure 4.21, LCRA structure data is stored in a polygon feature class. Each structure in this feature class has an attribute that records the structure's

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surveyed first-floor elevation. It is this elevation that must be compared to the water surface elevation in order to determine depth of inundation. Therefore, for this project, it was essential to extract the water surface elevation at the location of each structure.

A number of different methods for extracting the water surface elevation were considered. In the end, two important decisions were made. First, it was decided that structure polygons should be converted to points to make calculations simpler and execute more quickly. Second, it was decided that water surface elevations should be extracted from the water surface TIN, not the water surface raster. The reason for the second decision was that due to an inadequacy in the ArcGIS zonal statistics function, if two (very small) structures were located within the same raster cell, then the water surface would only be computed for one of the structures.

In the end, a complete procedure for calculating structure inundation depths was established. That procedure is outlined below:

1. Convert cross sections to a water surface TIN

2. Calculate the water surface elevation at each structure location

3. Subtract the first-floor elevation from the water surface elevation for each structure.

4. Export all records with a positive inundation to a flood damage table. (This table is a list of all inundated structures, and their depth of inundation)

Once the inundated structure table has been created, then statistics can be calculated to determine the total flood damage. These statistics are stored in a separate table where one record includes all of the statistics for the given flood event. For this research, only the number of structures inundated and the average depth of inundation were calculated. Economic data could be calculated in a similar manner.

4.3.4 Flood Data Model Development

Unlike Arc Hydro and the HMS IDM, this data model was not created using UML. Instead, it was created by manipulating the feature classes provided by the LCRA. The goal of this data model was to provide a repository for the maps and data calculated by the flood damage evaluation process, and to provide a location to archive these results at the user's discretion. An ArcCatalog view of this data model is shown in Figure 4.28. This data model was designed to work with the Model Builder procedure discussed in the following section.
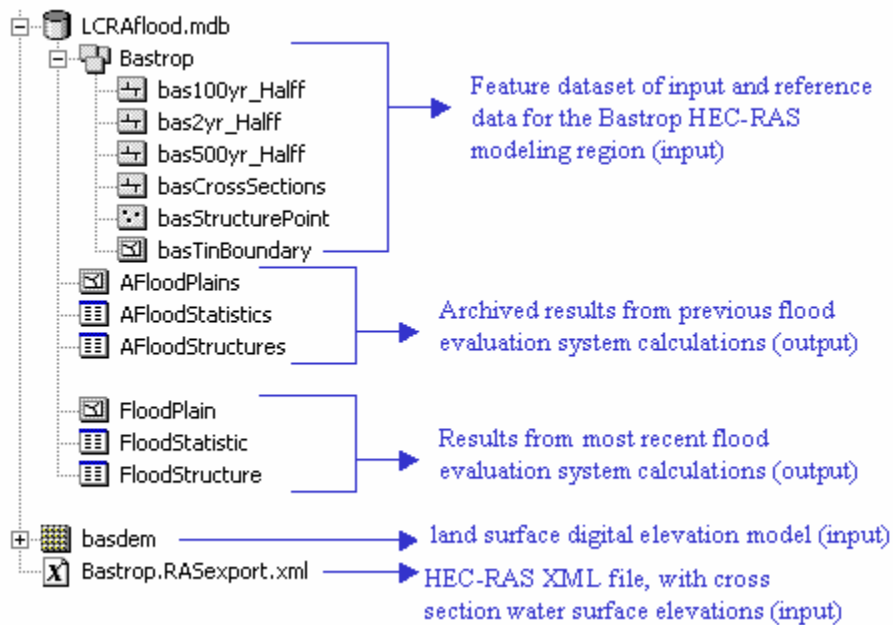
Figure 4.28 – Data model for flood damage evaluation

Most input data are arranged into feature datasets, where the name of the feature dataset equals the name of the corresponding HEC-RAS modeling area. The only essential data for these datasets are the StructurePoint and CrossSections feature classes. All other feature classes inside the datasets are used only for reference. Figure 4.28

includes only one feature dataset (Bastrop), but a complete model of the entire Lower Colorado River would include many more.

Output data reside in the six feature classes and tables that reside in the geodatabase, but outside of any feature dataset. The FloodPlain, FloodStatistic, and FloodStructure classes store the data resulting from the most recent calculations. When new calculations are performed, the data in these classes will be overwritten. The AFloodPlains, AFloodStatistics, and AFloodStructures classes store archived data. These classes include the results of many calculations, and individual scenarios are identified by the ModelID and EventID attributes. Figure 4.29 includes all of the classes and fields required by the flood damage evaluation system. Note that the CrossSections and StructurePoint feature classes have three-letter prefixes designating the study area (in this case, "trv" represents the Lake Travis study area).

Simple feature class
trvCrossSections

Geometry *Polyline*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Description	Precision	Scale	Length
OBJECTID	Object ID					
Shape	Geometry	Yes				
STREAM_ID	String	Yes	HEC-RAS stream name			16
REACH_ID	String	Yes	HEC-RAS reach name			16
STATION	Double	Yes	Cross section station location	0	0	
type	String	Yes	Cross section type - main stem or cove			20
Shape_Length	Double	Yes		0	0	
Max_WS	Double	Yes	Maximum water surface elevation for storm event	0	0	

Simple feature class
trvStructurePoint

Geometry *Point*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Description	Precision	Scale	Length
OBJECTID	Object ID					
Shape	Geometry	Yes				
STRUC_NAME	String	Yes	LCRA structure name			10
CALCELEV	Float	Yes	Calculated first floor elevation	0	0	
STATION	Double	Yes	Structure station location (optional)	0	0	

Simple feature class
FloodPlain / AFloodPlains

Geometry *Polygon*
Contains M values *No*
Contains Z values *No*

Field name	Data type	Allow nulls	Description	Precision	Scale	Length
OBJECTID	Object ID					
SHAPE	Geometry	Yes				
GRIDCODE	Double	Yes	Grid code (from raster)	0	0	
EventID	Long integer	Yes	Storm event identifier	0		
ModelID	Long integer	Yes	Model run identifier	0		
Description	String	Yes	Description of event/model			255
SHAPE_Length	Double	Yes		0	0	
SHAPE_Area	Double	Yes		0	0	

Table
FloodStatistic / AFloodStatistics

Field name	Data type	Allow nulls	Description	Precision	Scale	Length
OBJECTID	Object ID					
FREQUENCY	Long integer	Yes	Number of inundated structures	0		
MEAN_Depth	Double	Yes	Average depth of inundation	0	0	
MAX_Depth	Double	Yes	Maximum depth of inundation	0	0	
EventID	Long integer	Yes	Storm event identifier	0		
ModelID	Long integer	Yes	Model run identifier	0		
Description	String	Yes	Description of event/model			255

Table
FloodStructure / AFloodStructures

Field name	Data type	Allow nulls	Description	Precision	Scale	Length
OBJECTID	Object ID					
STRUC_NAME	String	Yes	LCRA structure name			10
CALCELEV	Float	Yes	Calculated first floor elevation	0	0	
STATION	Double	Yes	Structure station location (optional)	0	0	
Depth	Float	Yes	Calculated depth of inundation	0	0	
Spot	Double	Yes	Calculated water surface elevation	0	0	
EventID	Long integer	Yes	Storm event identifier	0		
ModelID	Long integer	Yes	Model run identifier	0		
Description	String	Yes	Description of event/model			255

Figure 4.29 – Classes and fields required for the flood damage evaluation system

4.3.5 Model Builder Application

Model Builder is a GIS graphical programming system available in ArcGIS 9. This system can be used to string together data, ArcGIS tools, scripts, and external programs into a single application. According to Tim Whitaker, a senior member of the CRWR research team, Model Builder can be used to create elaborate GIS applications in a fraction of the time that it would have taken using older programming systems (personal communication, 2004).

Model Builder uses a number of graphical symbols to represent different items in the modeling system. It is important to be familiar with these symbols to understand the modeling process. A list of these symbols follows:

1. Toolbox. All tools, models, and scripts must reside in a toolbox.
2. Toolset. Tools, models, and scripts may be organized into toolsets.
3. Model. All Model Builder processes are created as models.
4. Script. A script is written by the user; may be used as part of a model.
5. Tool. ArcToolbox processes; may be used as part of a model.

Model Builder can be used to create a customized toolbox where each tool is a user-defined model. The completed toolbox for this project is shown in Figure 4.30. As shown, the contents of this toolbox are arranged into five toolsets. The first three toolsets, which are numbered, include the primary tools which the LCRA would use on a regular basis. The "Components" and "Scripts" toolsets include sub-models and scripts that are called by the first three toolsets. All of these tools were designed in the "Pre-Release" version of ArcGIS 9. The remainder of this section describes these toolsets in greater detail.
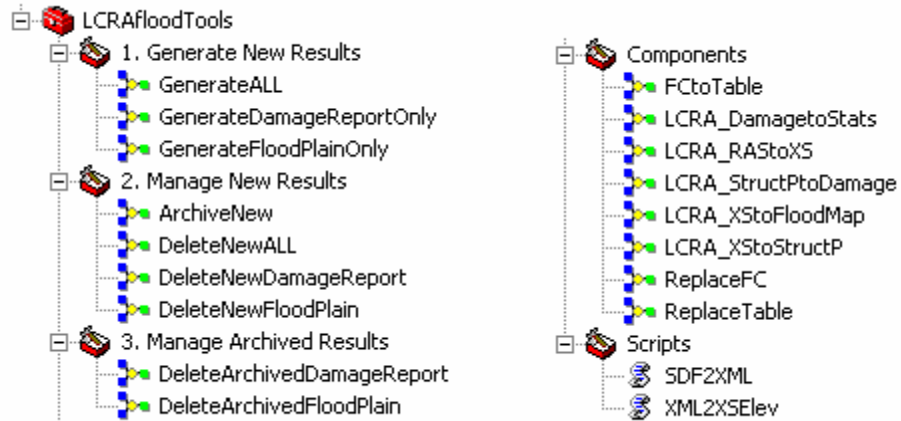
Figure 4.30 – Toolkit for the flood damage evaluation system

Generate New Results Toolset

This toolset includes the tools necessary to generate new results from the input data illustrated in Figure 4.28. These tools were designed to give the user the ability to generate a floodplain, a damage report, or both. By double-clicking on the GenerateALL tool, the GUI interface shown in Figure 4.31 appears. The inputs for this GUI are the four files necessary to create a floodplain map and damage report.
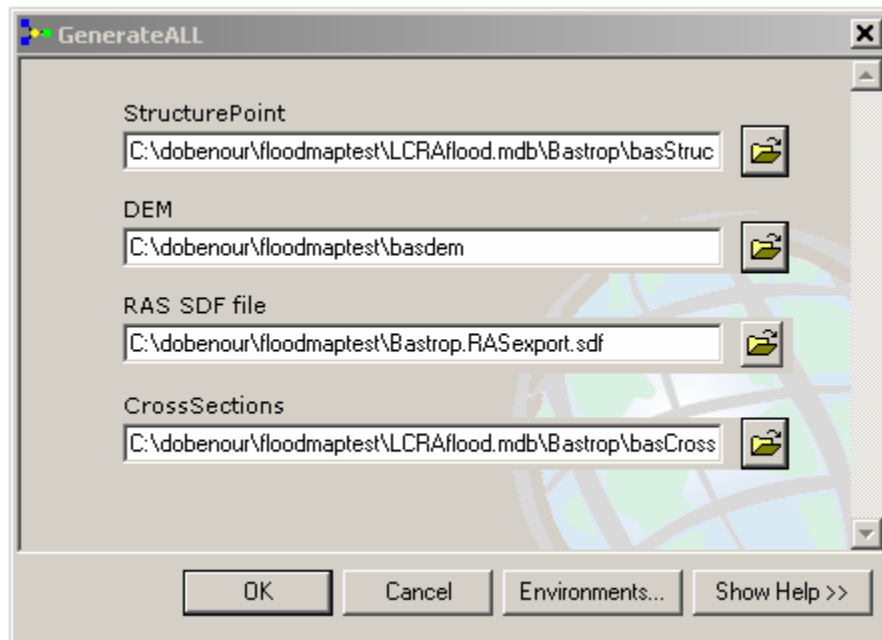
Figure 4.31 – GUI for the GenerateALL tool

The user can also view the inner workings of these models. For example, Figure 4.32 shows the layout of the GenerateALL model. As illustrated in this figure, data are represented as ovals, and processes are represented as rectangles. The four blue ovals on the left side of the diagram are the four model inputs. The green ovals are intermediate and permanent data products created when the model is run. In this model, each of the processes (yellow rectangles) represents another model (a sub-model) which is called by the GenerateALL model. These other models are stored in the Components toolset, as discussed previously.

Each of the sub-models may also be viewed. Figure 4.33 shows the insides of the LCRA_XStoFloodMap model. This model takes cross sections with assigned water surface elevations and the land surface DEM, and creates the floodplain map. In this model, each process is a Arc-GIS defined tool; this model has no sub-models.

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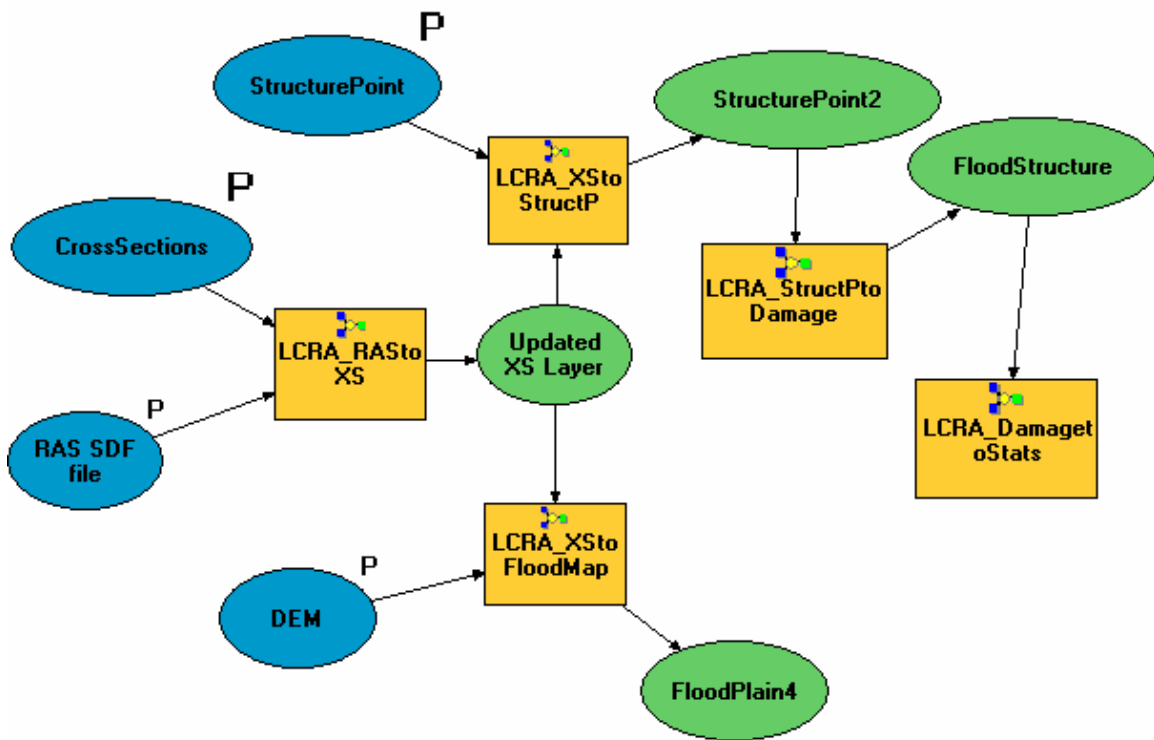
Figure 4.32 – GenerateALL model layout

The complete flood damage evaluation system toolbox contains many additional models. The general theory behind all of these models is very similar, however, and the concepts behind these models were defined in Sections 4.3.2 and 4.3.3. Therefore, a complete set of model layouts is not included in the body of this report, but is available in Appendix I.
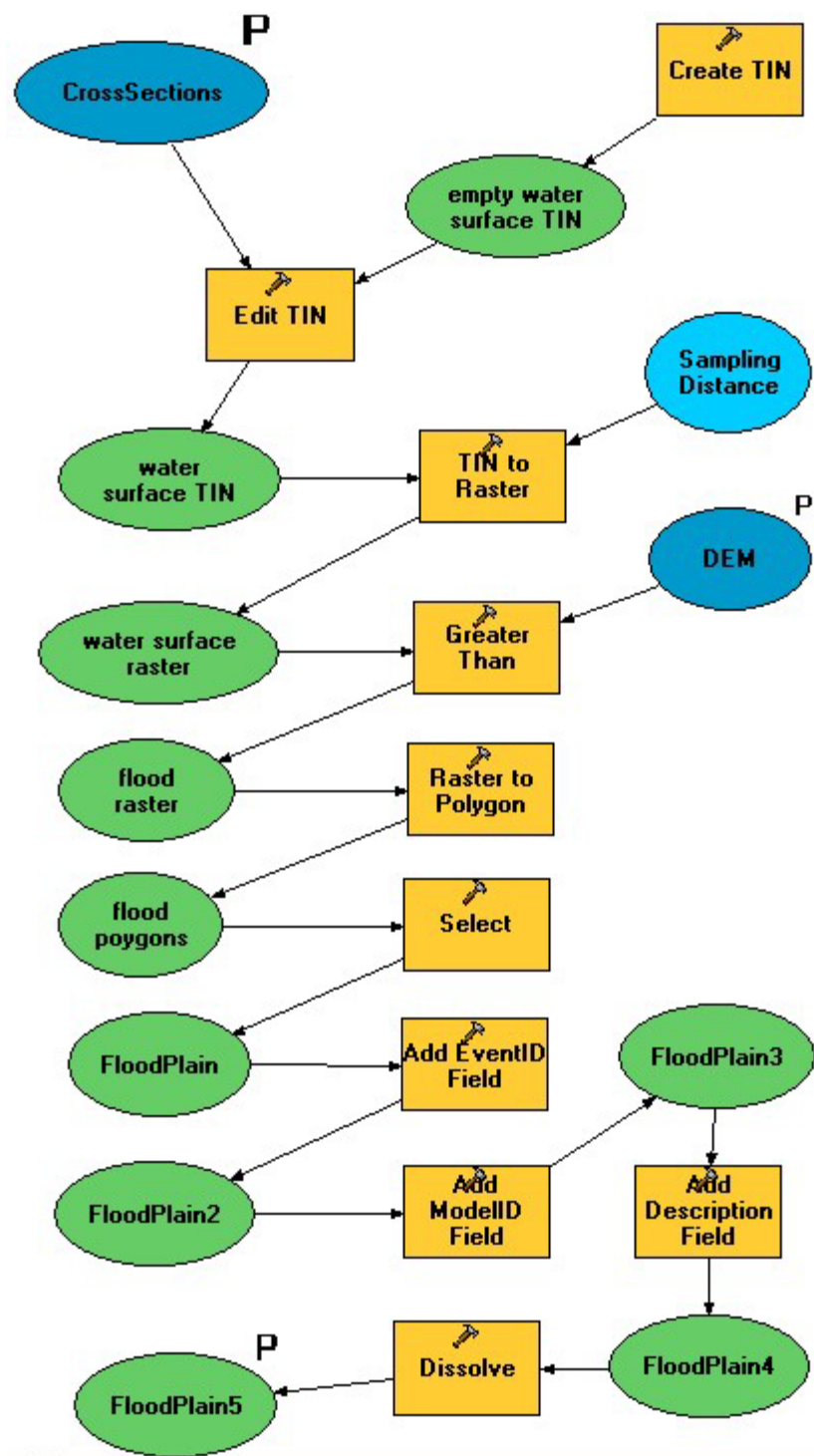
Figure 4.33 – Generate floodplain map model

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Manage New Results Toolset

Once new results have been created, they are temporarily stored in the FloodPlain, FloodStatistic, and FloodStructure classes. At this point, the user has the option to delete these results or to archive them. The "Delete" models clear all records from the tables, but do not delete the tables themselves. The archive model moves the results into the more-permanent AFloodPlains, AFloodStatistics, and AFloodStructures classes. It is at this point that the user can assign EventID, ModelID, and Description attributes in order to identify the particular set of results. In general, an EventID represents a storm event, and a ModelID represents a particular model run. Therefore, many unique ModelIDs can correspond to the same EventID. The description field is a text field that is arbitrarily populated by the user. The ArchiveNew GUI is shown in Figure 4.34. Because this model moves data from one standardized set of tables to another standardized set of tables, the user is not required to input the locations of these tables. This proved to be one significant advantage of using a standardized data model.
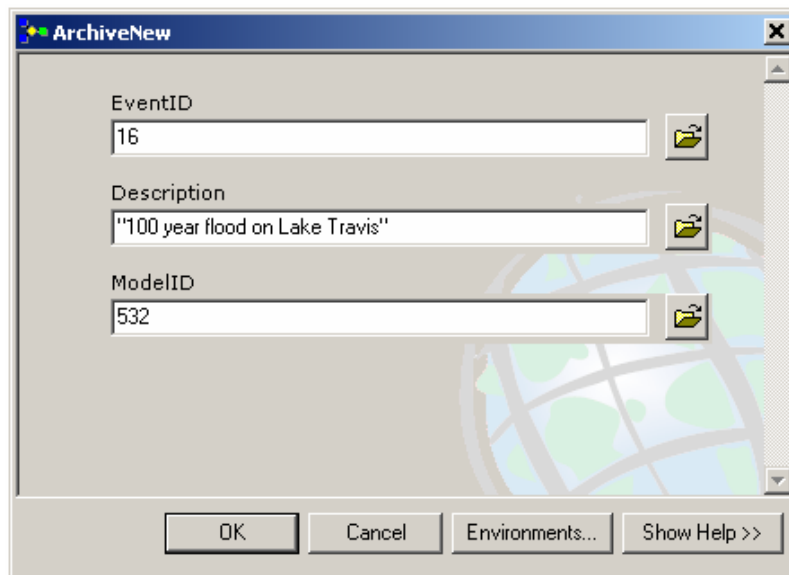
Figure 4.34 – GUI for the ArchiveNew model

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Manage Archived Results Toolset

The user may occasionally wish to delete archived results. To accommodate this, models were developed to delete records based on a query of the geodatabase. Because individual result sets are identified by the EventID and ModelID, it was assumed that most deletes would be based on these two fields. The GUI interface used for deleting archived floodplains is shown in Figure 4.35. By clicking on the file icon to the right of the text box, the user can build custom queries.
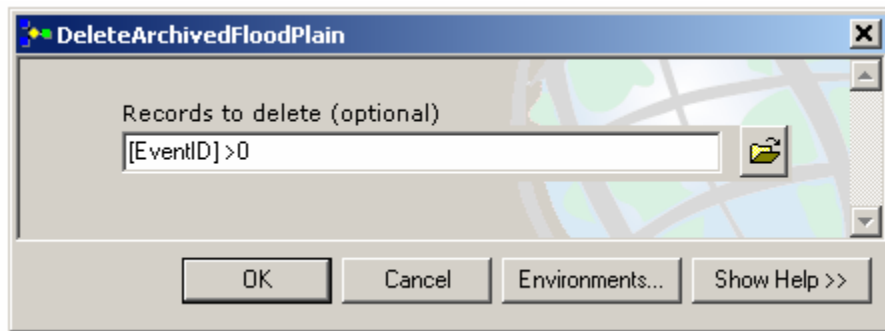
Figure 4.35 – GUI for the DeleteArchivedFloodPlain model

Components and Scripts Toolsets

These toolsets contain the most inner workings of this Model Builder system. Many of the models in the first three toolsets call the sub-models and scripts located within the Components and Scripts toolsets. These sub-models and scripts can be called by multiple higher-level models; and they thus reduce the need to create the same processes over and over again for each application. The scripts are used to take water surface elevations from the HEC-RAS SDF file, and assign them to the cross section feature class. They were developed by ESRI and modified at CRWR.

Toolbox Summary

Table 4.5 is a summary of the various models and scripts included in the LCRAfloodTools toolbox. This table includes the toolkit in which each model and script belong, and a list of sub-models that are called by these models. Table 4.6 lists the input data, output data, and purpose of each tool.

#	Model Name	Toolset	Sub-Models/ Scripts Called
1	GenerateAll	1. Generate New Results	11,12,13,14,15
2	GenerateDamageReportOnly	1. Generate New Results	11,13,14,15
3	GenerateFloodPlainOnly	1. Generate New Results	11,12
4	ArchiveNew	2. Manage New Results	
5	DeleteNewAll	2. Manage New Results	
6	DeleteNewDamageReport	2. Manage New Results	
7	DeleteNewFloodPlain	2. Manage New Results	
8	DeleteArchivedDamageReport	3. Manage Archived Results	17
9	DeleteArchivedFloodPlain	3. Manage Archived Results	16
10	FCtoTable	Components	
11	LCRA_RAStoXS	Components	18,19
12	LCRA_XStoFloodMap	Components	
13	LCRA_XStoStructP	Components	
14	LCRA_StructPtoDamage	Components	
15	LCRA_DamagetoStats	Components	
16	ReplaceFC	Components	
17	ReplaceTable	Components	
18	SDF2XML	Scripts	
19	XML2XSElev	Scripts	

Table 4.5: Summary of LCRAfloodTools

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#	Model Name	Inputs	Ouputs	Purpose
1	GenerateAll	DEM, SDF, StructurePoint CrossSection	FloodPlain FloodStructure FloodStatistic	Creates new flood map and damage report
2	GenerateDamageReportOnly	SDF, CrossSection StructurePoints	FloodStructure FloodStatistic	Creates new damage report
3	GenerateFloodPlainOnly	DEM, SDF CrossSection	FloodPlain	Creates new flood map
4	ArchiveNew	FloodPlain FloodStructure FloodStatistic	AFloodPlains AFloodStructures AFloodStatistics	Archives all new data
5	DeleteNewAll	FloodPlain FloodStructure FloodStatistic	n/a	Deletes all new data
6	DeleteNewDamageReport	FloodStructure FloodStatistic	n/a	Deletes new damage report data
7	DeleteNewFloodPlain	FloodPlain	n/a	Deletes new flood map
8	DeleteArchivedDamageReport	AFloodStructures AFloodStatistics	n/a	Deletes archived damage report(s) based on query
9	DeleteArchivedFloodPlain	AFloodPlains	n/a	Deletes archived flood map(s) based on query

Table 4.6: LCRAfloodTools input and output data

(continued on following page)

#	Model Name	Inputs	Ouputs	Purpose
10	FCtoTable	any	any	Converts feature class to table (not used by any other model)
11	LCRA_RAStoXS	CrossSection SDF	CrossSection2	Extracts RAS SDF water surface elevations, assigns to cross sections
12	LCRA_XStoFloodMap	CrossSection2 DEM	FloodPlain	Converts cross sections to a floodplain map
13	LCRA_XStoStructP	CrossSection2 StructurePoint	StructurePoint2	calcluates water surface elevation at all structures
14	LCRA_StructPtoDamage	StructurePoint2	FloodStructure	calculates depth of inundation for all structures
15	LCRA_DamagetoStats	FloodStructure	FloodStatistic	calculates flood statistics for inundated structures
16	ReplaceFC	any	any	replaces an existing feature class with a modified feature class
17	ReplaceTable	any	any	replaces an existing table with a modified table
18	SDF2XML	SDF	XML	converts .SDF file to .XML file
19	XML2XSElev	XML	CrossSection	converts .XML file to crosssection water surface elevations

Table 4.6: LCRAfloodTools input and output data (continued)

Chapter 5: Results

In many respects, the methodologies developed in Chapter 4 are some of the most important results of this research. Nonetheless, through these methodologies, a number of important end results were also created. These final products are the subject of this chapter. The three sections that follow discuss the results of the Arc Hydro data model, the HMS interface data model, and the GIS-based flood damage evaluation system.

5.1 ARC HYDRO RESULTS

This section discusses the results of applying the Arc Hydro system to the Lower Colorado River, and the Llano River specifically. First, the results of the Arc Hydro Framework for storing geospatial data are presented. Second, the Arc Hydro time series format is tested and evaluated. Finally, the Arc Hydro toolset is assessed.

5.1.1 Arc Hydro Framework

The development of the Arc Hydro Framework for the Llano River Basin was successful. All of the source data fit readily into the Arc Hydro data model, and although the development process was slow at first, once the author became familiar with the methods and theory behind the process, it went much more quickly. For an experienced user, the creation of an Arc Hydro Framework for an area the size of the Llano Basin should take days, not weeks. Figures 5.1 through 5.4 show ArcMap screenshots of the completed Arc Hydro data model.

Arc Hydro for The Llano Basin
January, 2003

Legend

HydroJunctions
- ·   MonitoringPoint
- •   WbdOutlet
- ◦   WshOutlet
- •   <all other values>

MonitoringPoints
- ▲   lake level+rain
- ▲   rain
- ●   stream
- ●   stream+rain
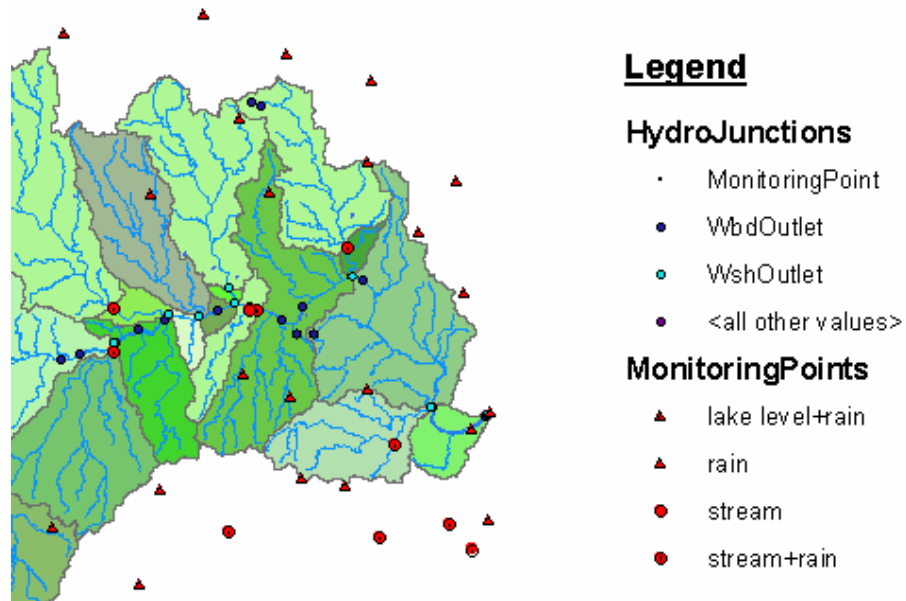
Figure 5.1 – Finished model, HydroJunctions & MonitoringPoints

Figure 5.2 – Finished model, feature Names/HydroCodes
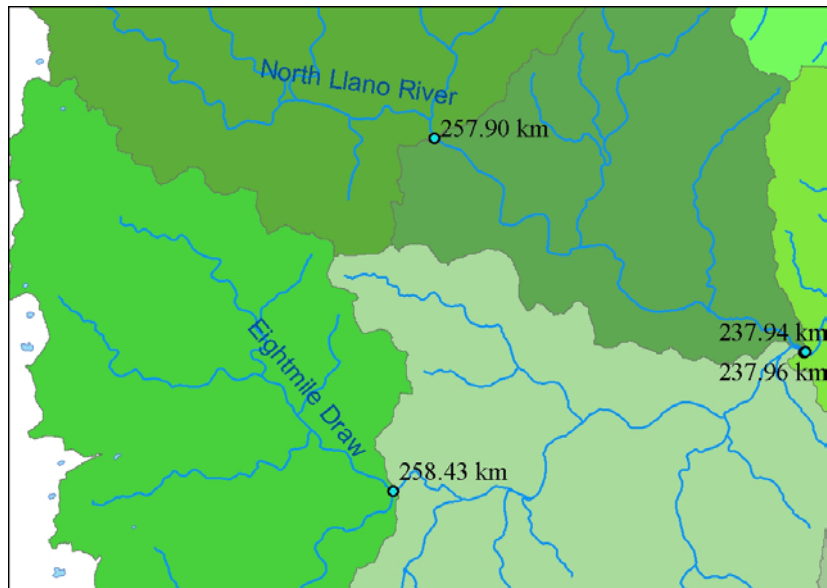
Figure 5.3 – Finished model, lengths from basin outlet
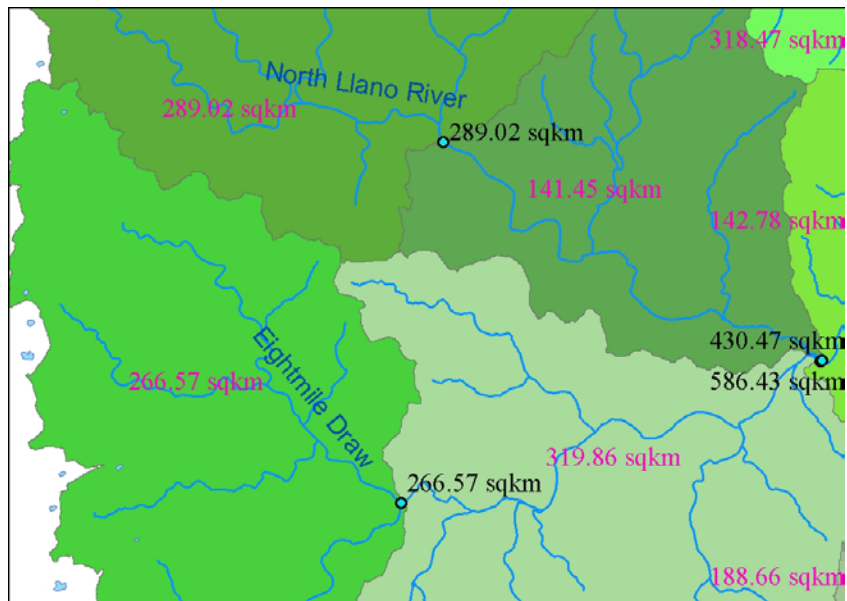
Figure 5.4 – Finished model, watershed areas & cumulative area upstream for junctions

Arc Hydro Network

According to *Arc Hydro – GIS for Water Resources*, "The hydro network is the backbone of Arc Hydro… The topological connection of its HydroEdges and HydroJunctions in a geometric network enables tracing of water movement upstream and downstream through streams, rivers, and water bodies." (Maidment, 2002). The network also provides a means of river addressing using the flow length between various points on the river network. The result of a trace upstream on the Llano HydroNetwork is shown in Figure 5.5.
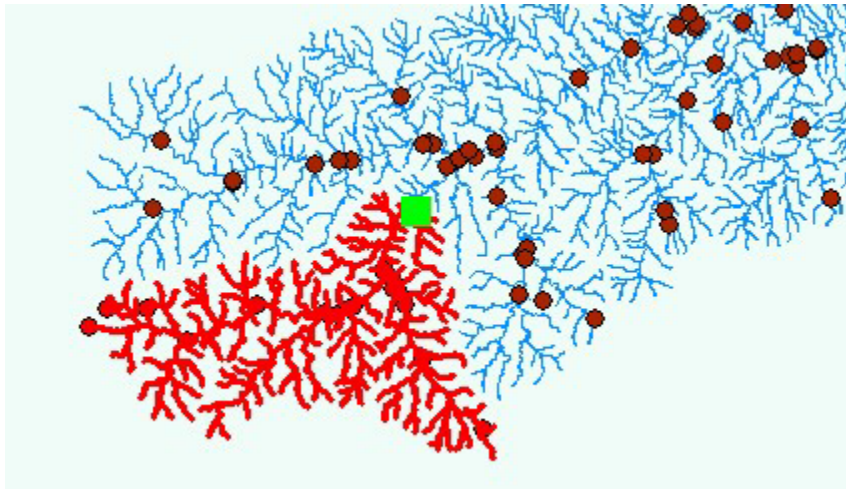
Figure 5.5 – Upstream trace from a "flag" placed southwest of Junction, Texas

5.1.2 Arc Hydro Time Series Format

For datasets of limited size, there are no functional limitations associated with the Arc Hydro time series format. However, for time series of larger sizes, computer software and hardware limitations become a problem. Most of the work in this project was performed on a computer with a 2.5-gigahertz processor and 1 gigabyte of random access memory (RAM). Nonetheless, the problems associated with large TimeSeries

tables (generally 1,000,000 records or larger) became very apparent throughout the course of this project. These problems included error messages, computer lock-up, and even inaccurate sort and query results. The full Hydromet Interval table (3,000,000 records) was successfully loaded into the Arc Hydro personal geodatabase but it had no functionality using standard ArcGIS tools due to its large size.

Similar problems were experienced when working with the NEXRAIN data. Only for small datasets, could NEXRAIN data can be successfully imported into ArcHydro and viewed using the Time Series Viewer animation tool. Figure 5.6 shows snapshots from an animation of NEXRAD (similar to NEXRAIN) data over the Llano River watershed. The time series used for this animation consisted of 5,000 records. Larger time series can be used, but they require considerable time to prepare and can result in choppy animations.
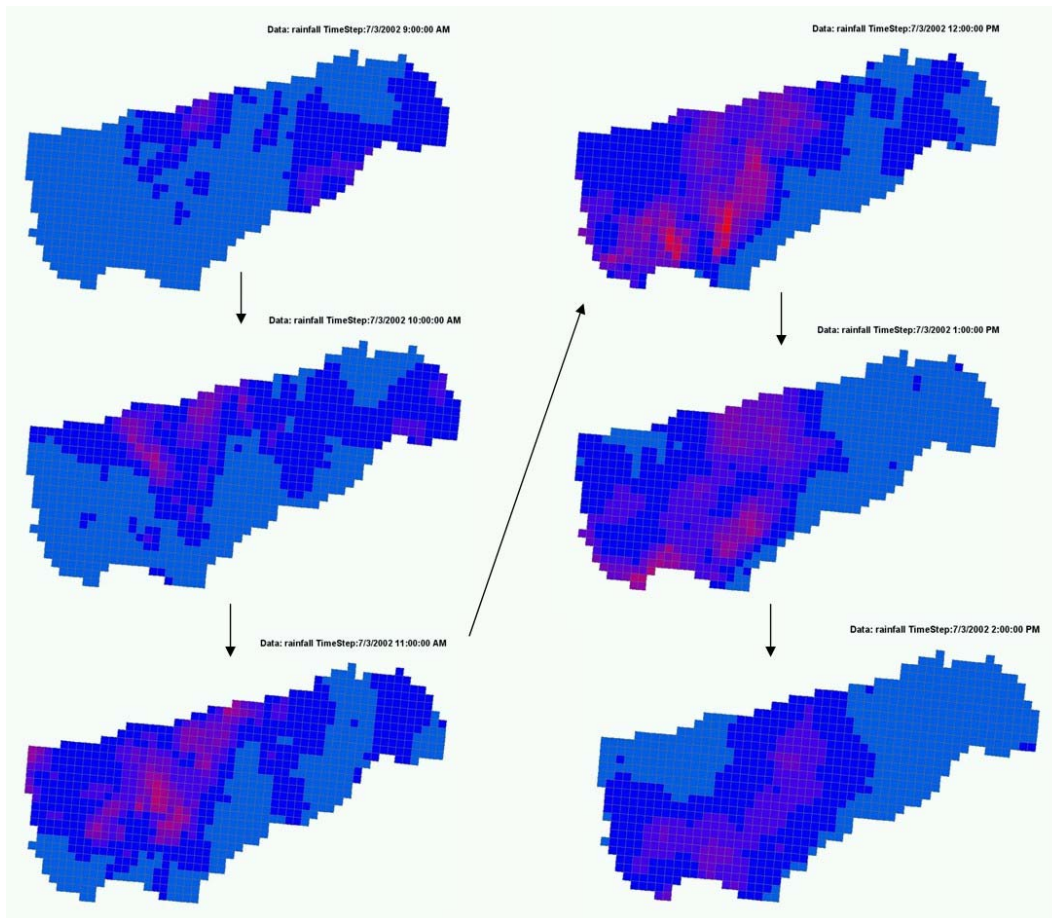
Figure 5.6 – Screen captures of a storm event moving over the Llano Basin

Arc Hydro Time Series in SQL Server

Originally, it was anticipated that storing time series in SQL Server would prove much more efficient than storing time series in the personal database format. However, due to imperfections in ESRI's ArcSDE software, this has yet to be verified. One problem is a SDE log table that creates a record for every object queried (selected) by the ArcMap user. When querying a large selection of time series data, this log table grows to an immense size that causes the server to crash. Another problem is the slow

performance of queries made through the ArcMap/SDE interface. (An example query: Select from the TimeSeries table all records that have a FeatureID equal to 16.) A query made through the ArcMap/SDE interface can take many times longer than an identical query made through a non-SDE database connection (i.e. a MS Access ODBC connection). The staff at CRWR, as well as at the LCRA, has put forth considerable effort attempting to resolve these problems, but so far, no solution has been found. A dialogue between ESRI and CRWR was initiated with the purpose of resolving these ArcMap/SDE time series issues. The ESRI staff believes that ArcSDE can be used effectively, and can meet the needs of CRWR (personal communication, Hugh Keegan - ESRI, 2003). Therefore, this issue will continue to be investigated.

Testing Arc Hydro Time Series Performance

To quantify these findings, a thorough analysis was conducted using LCRA Hydromet data and the computers at CRWR. The Hydromet data included 11 years of flow, stage, and precipitation data with a one-hour time interval, recorded at various locations throughout the Lower Colorado River basin. This dataset included approximately 3,000,000 time series records (stored in the Arc Hydro time series format).

The personal computer used for this analysis had a 3.2 GHz processor and 1.5 GB of RAM. The SQL Server used for this analysis had dual 2.4 GHz processors and 1 GB of RAM. The Hydromet data was loaded onto a personal geodatabase on the personal computer and onto an ArcSDE geodatabase on the SQL Server. Once loaded, both of these data sources could be queried either from the Microsoft (MS) Access environment or the ArcGIS environment.

Two queries were used to test the performance of these data sources. The first query was a selection of all records whose FeatureID=14 that resulted in approximately

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64,000 records. The second query was a selection of all records whose TSTypeID=11 that resulted in approximately 700,000 records.

These queries were attempted using a number of different methods, which are listed below:

1. ArcMap "Select by Attribute" query
2. ArcCatalog "Load Data" query
3. ArcToolbox/Model Builder "Select Table" query
4. MS Access "Make Table" query
5. Visual Basic query script

As discussed previously, the first two methods, which represent the most common ArcGIS methods for querying data, were not successful under any circumstances. The ArcGIS software crashed when either of these methods was attempted. The third, fourth, and fifth, methods were successful. However, it was determined that the fourth and fifth methods were effectively the same because query times for these two methods were virtually identical, and both methods used MS Access functionality. In summary, there were two methods that were successful:

1. ArcToolbox/Model Builder "Select Table" query
2. MS Access query

Figure 5.7 shows query times for the two methods listed above: "ArcToolbox" and "MSAccess" queries. These queries were performed on both the personal and SQL Server geodatabases. In general, queries using the MS Access method were faster than queries using the ArcToolbox method. Also, queries on the SQL server were faster than queries on the personal geodatabase. For the large query (700,000 records) the advantage of using SQL Server appears to be relatively small, but this could be a result of the fact that the CRWR SQL Server has less RAM than the personal computer.
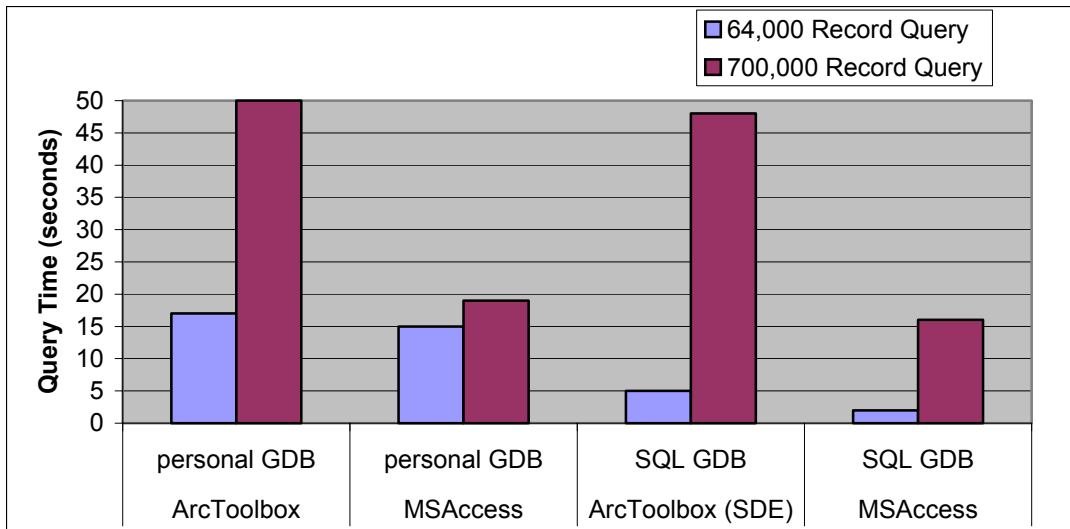
Figure 5.7 – Time series query performance under various conditions

Evaluation of the Arc Hydro Time Series Format

The Arc Hydro format was used extensively by this research. In this format, all time series time/value combinations are stored in one table along with their geographic reference (FeatureID) and data type (TSTypeID). The ability to relate time series data directly to their corresponding features proved to be one major advantage of the Arc Hydro time series format, especially when attempting to create time series animations.

There are, however, limitations associated with the Arc Hydro time series format. One difficulty arises from the Arc Hydro concept of storing all time series data within just one table. This creates two potential problems. First, if all data must be stored within just one table, then that table may grow to a size that that hinders system performance. Also, attempting to store permanent archived time series data in the same table where new time series data are being generated could produce a tenuous situation. If an error occurs while the new data is being generated, then potentially, the entire table of data could be lost (this is a particularly significant concern in the research

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environment). Therefore, for most time series work performed during this project, multiple time series tables were created in order to improve the stability and performance of the data model.

In order to create time series animations using the Tracking Analyst, each unique time series type must be stored in a unique table. If time series data of multiple types (multiple TSTypeIDs) are stored in the same table and related to the same feature, the Tracking Analyst will not be able to differentiate between the different data types. Therefore, when creating time series animations, it was generally necessary to export the relevant time series data into a unique, temporary time series table.

Another limitation of the Arc Hydro time series is that it is not optimized to meet the needs of specific datasets. In order to accommodate the widest range of data possible, each time series record uses data types that require considerable amounts of memory. If the time series format was compacted, as shown in Table 5.1 (for example), using smaller data types, then the amount of disk space required would be cut by one third. However, this format limits the accuracy and range of some of these variables.

Variable	AH Time Series Standard		AH Time Series Compact	
	data type	bytes	data type	bytes
FeatureID	Long	4	Short	2
TSTypeID	Long	4	Short	2
TSDateTime	Date/Time	8	Date/Time	8
TSValue	Double	8	Single	4
Total		24		16

Table 5.1: Arc Hydro time series format: standard and compacted

5.1.3 Arc Hydro Toolset

The Arc Hydro toolset includes many different sets of commands located under different menus. Figure 5.8 shows the toolbar menu options. For this research, only the "Terrain Processing", "Attribute Tools", and "Network Tools" were used extensively. An evaluation of these three sets of tools is included in this section. In general, all of these tools yielded correct results. However, this section discusses ways in which tools can be modified to make them more intuitive and useable.

Figure 5.8 – Arc Hydro toolbar

Terrain Processing Tools

These tools take a raster DEM and covert it into a set of vectorized watershed features, as discussed in Section 4.1.2. The primary difficulty with these tools is the amount of time that they take to execute. Many of these tools can take on the order of one-hour to complete. At times, it is difficult to tell whether the tool is operating correctly or whether the program has crashed. Also, because these tools require little user input, it would be advantageous to have the option to run these tools while the user is away (i.e. nights and weekends). For these reasons, the following improvements to the terrain processing tools could be very beneficial:

1. Create progress bars (Figure 5.9) that track the operation of these tools

2. Create a "master" tool that will run the entire series of individual terrain processing tools without the user present.
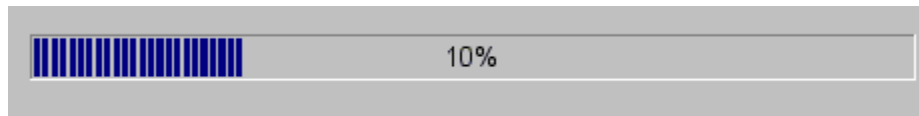
Figure 5.9 – Progress Bar

Attribute Tools

These tools are used to assign Arc Hydro attributes such as HydroIDs and downstream lengths. In general, these tools were very useable and very important to this project. Most of the tools are discussed in further detail in the tutorial of Appendix D. One tool that could potentially be improved is the "Store Area Outlets" tool, used to assign the HydroIDs of Watershed/Waterbody features to their respective HydroJunctions. Using the current version of this tool, a search is performed in the vicinity of each Watershed/Waterbody to determine which HydroJunction most accurately reflects the area's outlet. However, this tool sometimes makes inaccurate HydroJunction assignments (i.e. a HydroJunction that is supposed to be assigned to a Waterbody ends up assigned to a Watershed instead). If the tool was modified so that it only searches through HydroJunctions of a specific FType (which records whether the HydroJunction represents a Waterbody or Watershed), then many inaccurate assignments could be avoided.

Another limitation of these tools is that they are not well documented in any publicly available literature. Such documentation would be very important for users who are not familiar with Arc Hydro concepts. Some documentation of these tools is included in Appendix D of this report.

Network Tools

The network tools can be used to create schematic networks and to assign network flow directions. For this project, no schematic network was created, but flow

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directions were assigned to the HydroEdge/HydroJunction network. In general these flow directions are stored in two places: the "FlowDir" field of the HydroEdge feature class and inside the geometric network class. In addition to these sources of flow direction, the direction in which the HydroEdge lines were digitized may also represent the correct flow direction. The two tools used for assigning/transferring flow direction values are listed below:

1. "Store Flow Direction" takes the flow direction values stored in the geometric network, and transfers these values to the FlowDir field in the HydroEdge feature class.

2. "Set Flow Direction" assigns flow direction values to the geometric network. This assignment may be based on the values stored in the FlowDir field, or it may be based on the direction in which the HydroEdges were originally digitized.

The names "Store Flow Direction" and "Set Flow Direction" do not provide the user with an intuitive understanding of what each tool does. In fact, confusion between the purposes of these two tools proved to be a nuisance throughout the course of this project. It would be advantageous to replace these two tools with one concise and intuitive tool named "Transfer Flow Direction", which would have the ability to perform all desired flow direction value transfers. The GUI for such a tool might look something like Figure 5.10
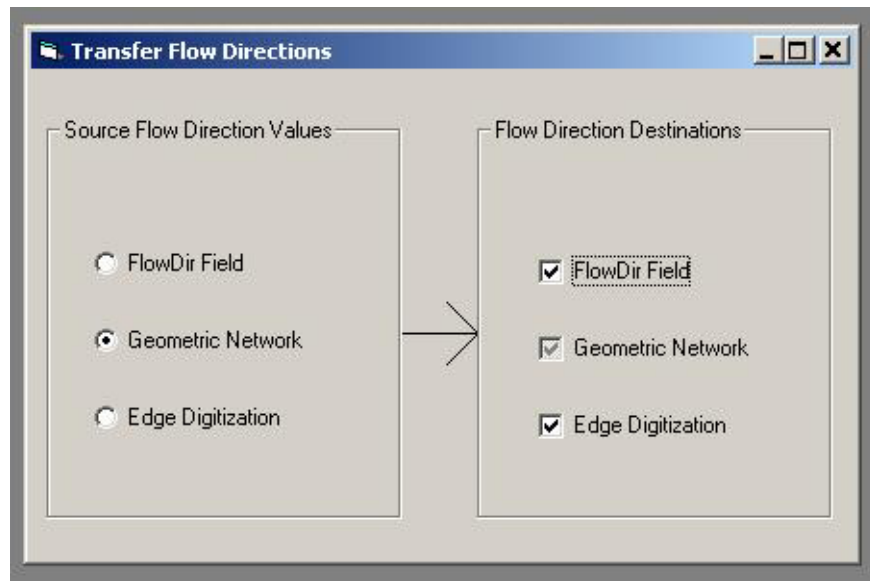
Figure 5.10 – Prototype "Transfer Flow Direction" GUI

5.2 HMS IDM RESULTS

Data from the LCRA/Halff HEC-HMS model for the "Llano River at Junction" were imported into the IDM to test its functionality. Data from HMS text files, such as the basin and control files, could be imported into the IDM almost instantly. DSS data could take longer, primarily due to the quantity of data that needed to be written to the geodatabase. Figure 5.11 to 5.14 show ArcMap screen captures of the completed IDM.
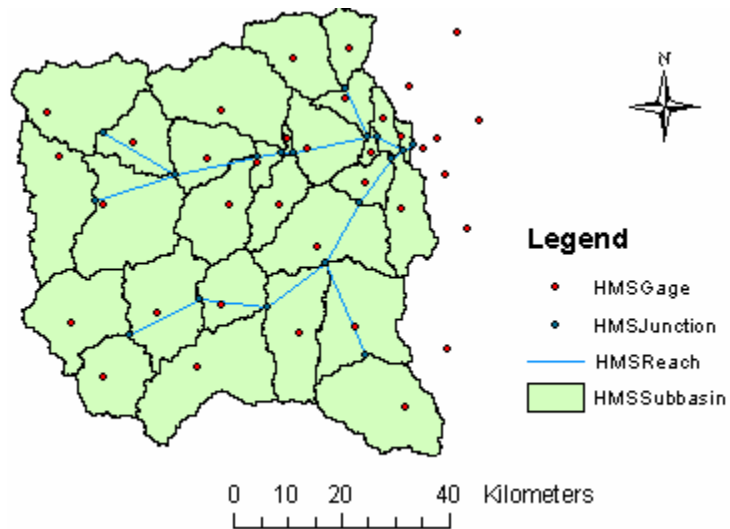
Figure 5.11 – ArcMap view of the Llano at Junction HEC-HMS Basin
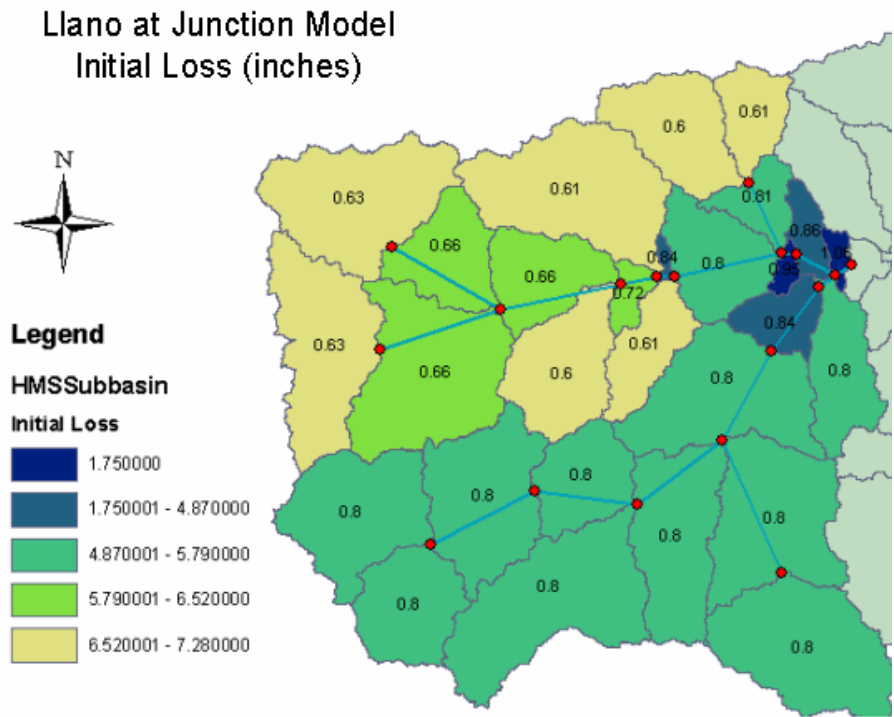
Figure 5.12 – ArcMap view of initial loss values for Llano at Junction Basin
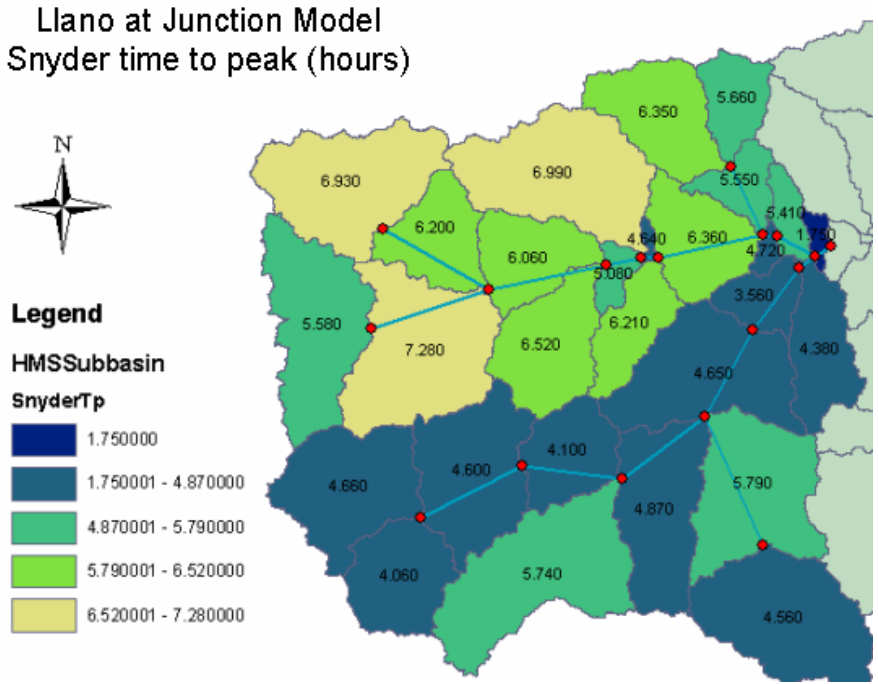
Figure 5.13 – ArcMap view of Snyder peaking times values for Llano at Junction Basin
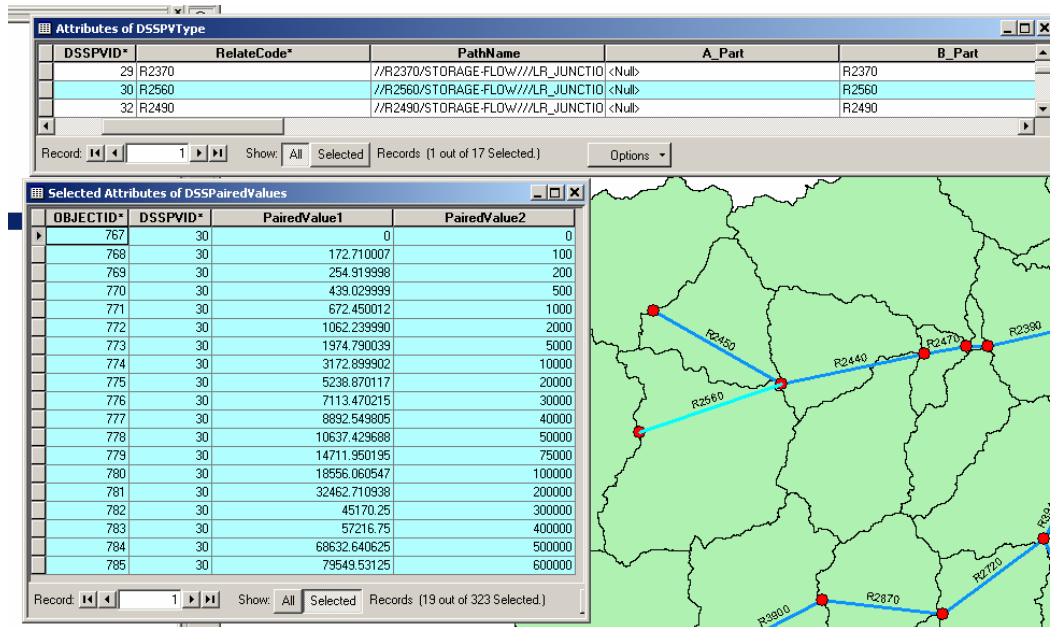
Figure 5.14 – A query of a paired data routing table for a reach in the Llano at Junction
Basin

The ability to use DSS time series within GIS was another important result of this
project. The time series component of this project has already been used in other
research, including the Map2Map application, developed at CRWR, which takes a
precipitation map and uses the HEC models to generate the resulting floodplain map
(Robayo, 2004). A query of time series in the HMS IDM is shown in Figure 5.15.

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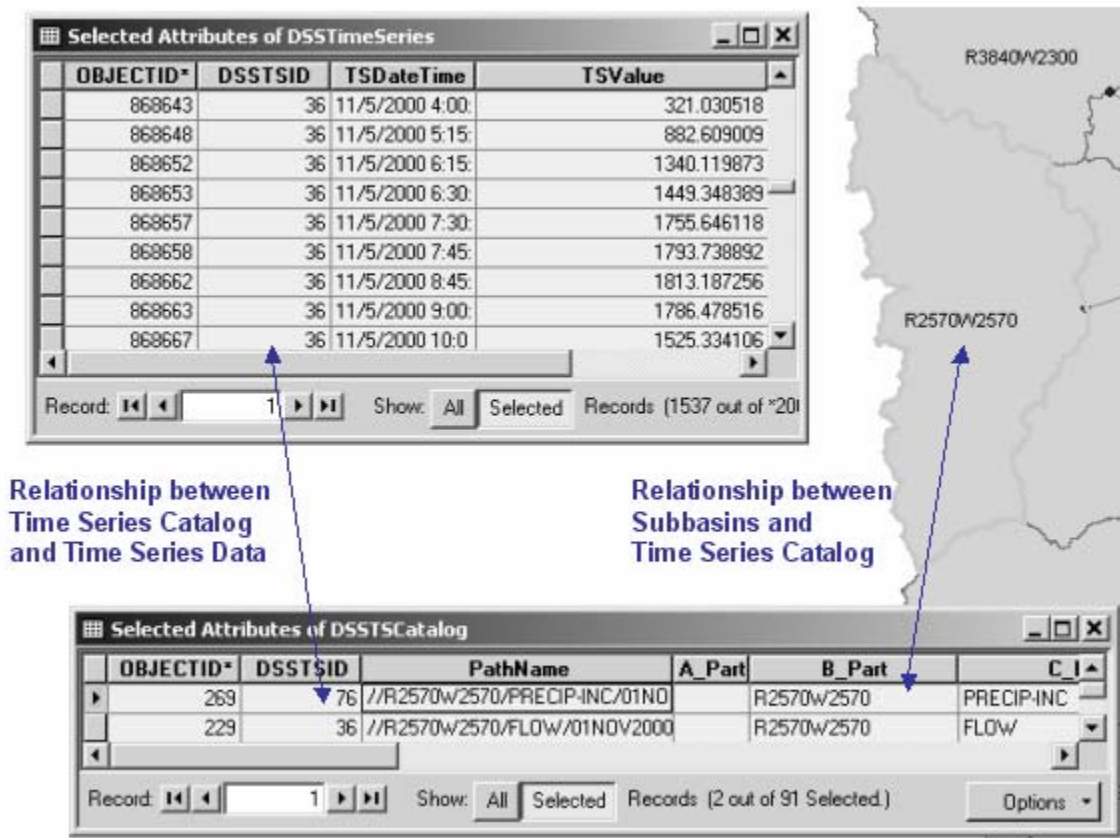
Figure 5.15 – Query of time series data for a particular HMS Subbasin

Using the HMS IDM and ESRI's Tracking Analyst Extension, a time series animation was developed to display the changing level of rainfall and stream flow occurring during a storm event. This was a relatively straightforward process, requiring little data manipulation. Although, the relevant time series data did have to be selected, and extracted into a smaller table, with a HMSCode field. Screenshots from this animation are shown in Figure 5.16

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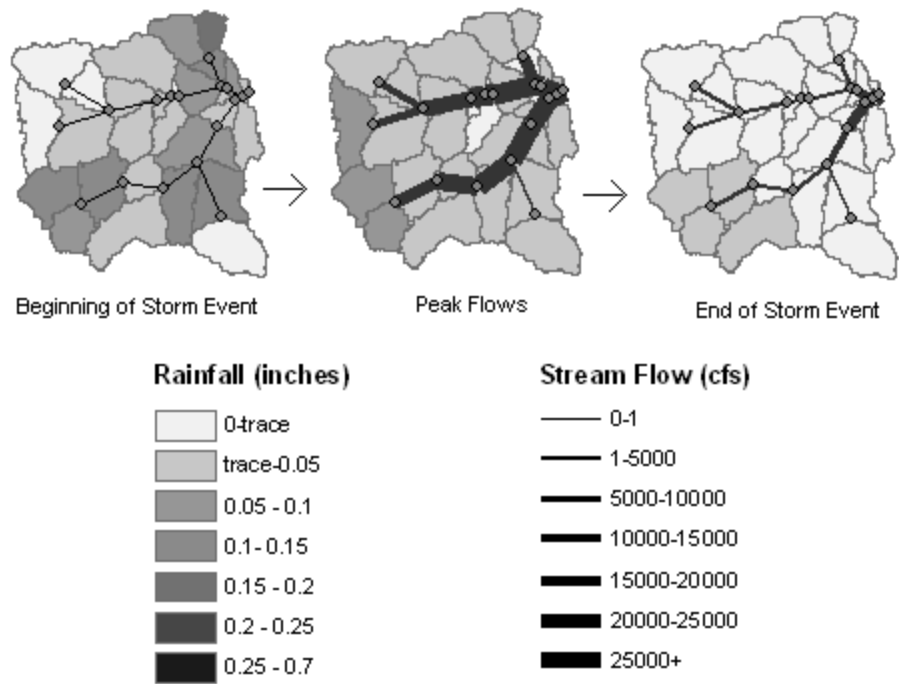
Figure 5.16 – Time series animation of IDM data (1 hour time step)

5.3 FLOOD DAMAGE EVALUATION SYSTEM RESULTS

The flood damage evaluation system was evaluated using two unique sections of the Lower Colorado River. The first section tested was Lake Travis, which is a reservoir with a virtually flat water surface profile, relatively high sinuosity, and a large number of coves. The second section tested was the Colorado River near Bastrop, which is an uncontrolled section of river with a relatively steep water surface profile (3/10,000 for 100-year flood), moderate sinuosity, and a large number of coves.

Floodplain maps

The floodplain maps generated by this project are based on the same hydraulic modeling data used by Halff and Associates for the creation of their maps. However, the land surface DEMs and cross sections were different. The DEMs used by this project were derived by converting the TINs created by Halff and Associates into rasters of considerably lower resolution. The cross sections used by this project were similar to those used by Halff, but modified as discussed in Section 4.3.

A comparison of the floodplain maps generated by this project to the floodplain maps generated by the Halff project is shown in Figure 5.17. This figure shows that at small scales, there is virtually no difference between the two floodplain maps. However, at relatively large scales, slight variations in the lines can be discerned. In fact, differences between the two maps can be as great as 8 meters (but are generally less than 4 meters), as shown in Figure 5.18. Also, when viewed at larger scales, the rough gridded edges of the floodplain polygon begin to show. These rough edges are a result of the fact that the floodplain polygon was created based on a raster. Rough edges can be avoided, however, as shown in Figure 5.18, by using the ArcGIS "generalize" option.

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The LCRA has the option to produce these maps using either the gridded or generalized method; there was no significant difference in performance.
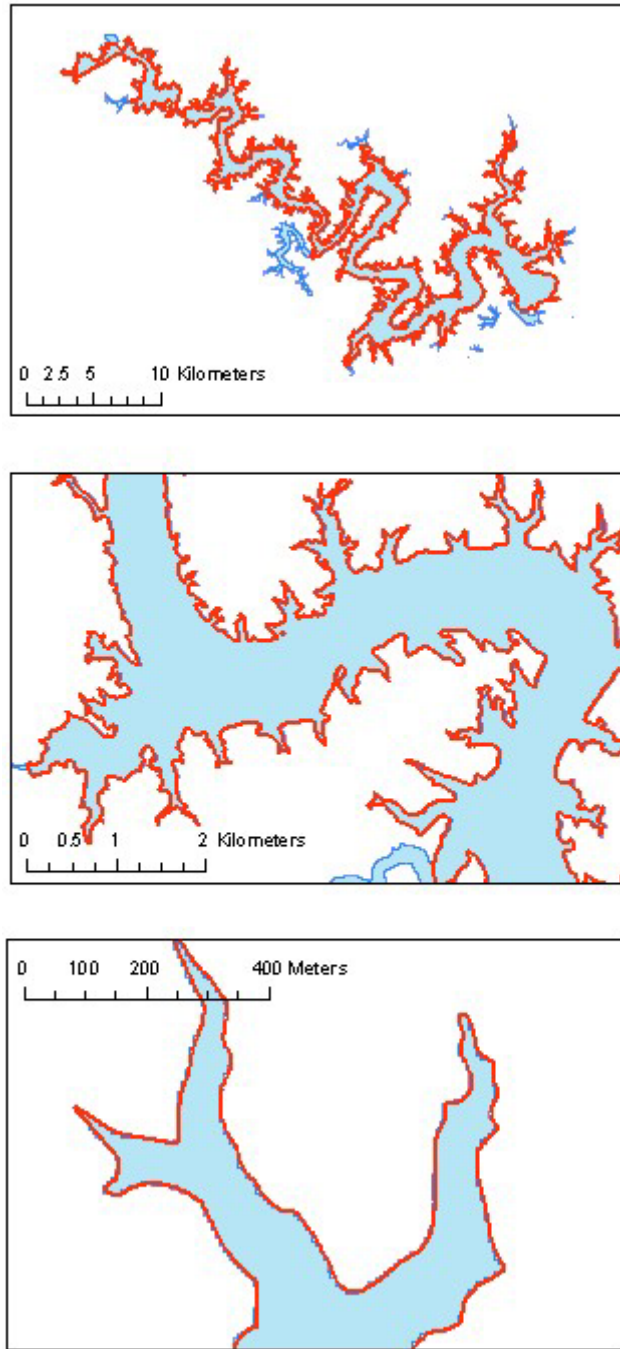
Figure 5.17 – Comparison of Halff floodplain (red line) to research results (blue polygon) at different scales, Lake Travis
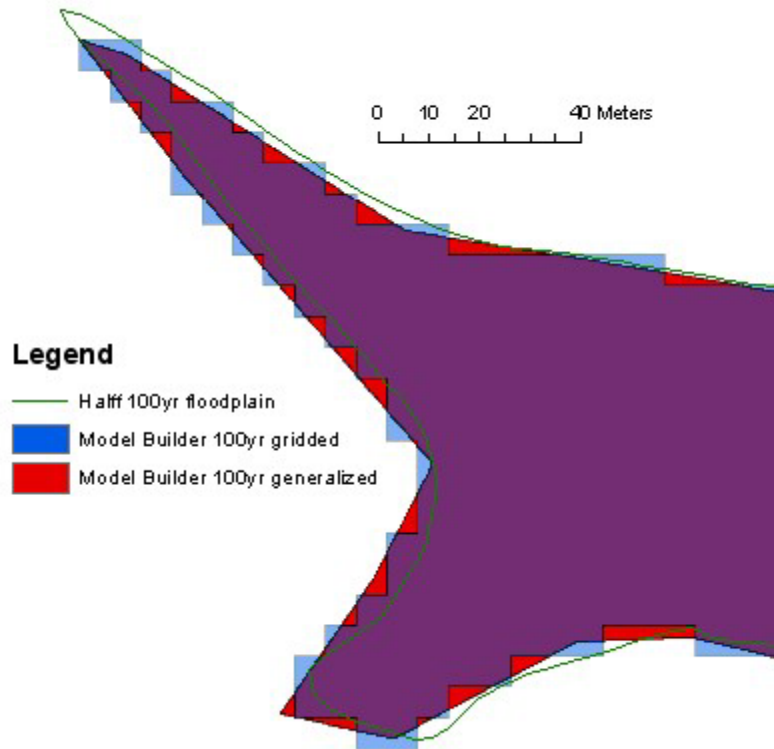
Figure 5.18 – Comparison of different floodplain maps at large scale, Lake Travis

As demonstrated by the preceding figures, the floodplain maps generated by the Halff method tend to be smoother and of slightly higher resolution. However, it is suspected that any large differences between the maps (over 5 meters), is more a result of different grid orientations, than errors in the mapping procedures. The primary advantage of the system developed by this research is the time that is saved in the map production process. First, these maps are generated in around 3 minutes (depending upon computer hardware) compared to the many hours required by the Halff method of TIN intersection. Second, the method developed by this research does not require manual editing of cove areas.

Damage Reports

Damage reports were also generated using the procedures developed by this research. These results have not yet been compared to other damage studies. However, the functionality of this Model Builder procedure has been well tested. Lists of inundated structures were generated, and statistics tables were calculated to summarize the results. Figure 5.19 shows an example of results for the 2-year flood at Bastrop. The fields shown in these tables are described in Figure 4.29.

Attributes of FloodStatistic

OBJECTID*	FREQUENCY	MEAN_Depth	MAX_Depth
1	55	3.986379	22.286011

Attributes of FloodStructure

OBJECTID*	STRUC_NAME	STRTYPE	CALCELEV	STATION	Depth	Spot
1	453-012443	0	408	1542255.25	12.2149	420.214905
2	021-000830	1	340.72	1261696.75	1.6145	342.334503
3	021-000831	1	339.36	1261607	2.96841	342.328400
4	021-000845	21	333.62	1258854.875	8.53448	342.154480
5	453-012650	0	420.79	1556042.625	2.44186	423.231873
6	453-013583	0	386.32	1438723.5	2.01001	388.330017
7	453-013584	0	387.6	1438723.5	0.698334	388.298340
8	453-015407	0	385.23	1427636.875	0.11441	385.344421
9	453-015161	0	385.33	1431243.125	0.352478	385.682465
10	453-015450	0	384	1426658.5	1.23276	385.232758
11	021-000183	1	376.56	1400673.125	2.48267	379.042664
12	021-000201	1	378	1400212.25	0.981018	378.981018
13	021-000203	1	372.7	1400138	6.26068	378.960693
14	021-000243	1	368.02	1378158.25	4.67419	372.694183
15	021-000351	1	349.2	1300476.125	1.37888	350.578888
16	021-000802	1	341.74	1260801.625	0.568909	342.308899
17	021-000805	1	340.05	1260751.5	2.25046	342.300446
18	021-000818	1	340	1260771.5	2.29468	342.294678

Figure 5.19 – Flood statistics and a portion of the inundated structures list for the 2-year flood of the Colorado River at Bastrop

Visualization of Results

The data that results from the flood damage evaluation system can be used in a number of ways. It can be used in analysis of different flood control alternatives and in reports. It can also be used to create effective GIS visualizations. An example of such a visualization is shown in Figure 5.20. This graphic was created using ESRI's ArcScene, and required relatively little data manipulation.

Figure 5.20 – 3-D visualization of inundated structures on Lake Travis

Chapter 6: Conclusions and Recommendations

6.1 PROJECT SUMMARY

This project examined different ways to apply Arc Hydro concepts to the Lower Colorado River basin. First, the Arc Hydro Framework was populated with general information that describes the Llano River basin. This process included the collection and transformation of existing GIS data and time series data maintained by the LCRA. The result of this work is a connected and manageable data repository based on the standardized Arc Hydro data format, which is now recognized nationwide.

Next, an interface data model was developed to store information specific to a particular hydrologic computational model, HEC-HMS. The resulting "HMS IDM" is considerably more complex than the standard Arc Hydro data model because it reflects the entire HMS program. Once developed, the IDM was tested with data from the LCRA's existing HMS models.

Finally, a GIS-based flood damage evaluation system was developed in order to provide a method for calculating flood analysis results based on terrain, structure, cross section, and HEC-RAS output data. Furthermore, a new data model was developed in order to store the input, output, and archived data that are a part of this system. ESRI's Model Builder system was utilized to develop the routines necessary to automate the analysis and archiving process.

To improve the results of the flood damage evaluation system, it was recommended that cross section geometries be modified to produce smoother, more accurate, and more complete water surface DEMs. This report includes the methods and concepts behind this modification process. In fact, this modification was completed for

the Lake Travis and Bastrop study areas of the Lower Colorado River basin. Finally, the flood maps generated by this research were compared to flood maps generated by a previous study.

6.2 PROJECT CONCLUSIONS

A number of conclusions were reached throughout the course of this project. A summary of these conclusions is included as follows:

Arc Hydro Framework and Time Series

1. The Arc Hydro Framework provides considerable advantages over the traditional, structureless methods of storing GIS hydrological data. It provides a method of stream addressing, querying of related data, and the ability to trace and select upstream and downstream on the stream network. The framework also provides a basic data structure which H&H models and other analysis tools may be designed in the future.

2. There is no reason to believe that the implementation of an Arc Hydro model for the entire Lower Colorado River basin would not also be successful. The methodologies developed for the Llano River basin are equally applicable to a basin of larger-scale. Throughout this project, it was determined that the Arc Hydro data model was most effective for storing permanent, general data describing the river basin, but not as effective for storing the more particular and dynamic data produced by computational models.

3. Limitations were discovered when working with time series data. For small data sets (generally less than 1,000,000 records in size) the Arc Hydro format was effective, in that the data could be queried and manipulated efficiently. However, time series datasets of larger size could not be used in the ArcMap environment,

regardless of whether the data were stored the personal database the server database (SQL). Hardware limitations were the primary reason for these deficiencies, although in the case of the server database, a shortcoming in the ArcSDE software was the greatest problem. Queries outside of the ArcMap environment, using either ArcToolbox or MS Access proved to be successful methods for working with these larger datasets.

4. The Arc Hydro time series format is effective because it can store a wide range of different time series types. Conversely, because of the generality of this format, it is not optimized for any particular type of data. Storing all time series data within one table provides a simple data structure, but it can also decrease system performance, reliability, and ease of use.

5. The Arc Hydro tools produce accurate results and perform reasonably well. However, a few modifications have been suggested in order to make the tools more intuitive and require less user input.

Interface Data Model

6. This was one of the first times that a computational model designed independently of GIS has been fit entirely into the ArcGIS world. The interface data model (IDM) has the ability to store all of the information required to run a HMS project. It also has the ability to store all of a project's results.

7. At the present, the primary benefit of the IDM is the ability to maintain and archive model results within a geodatabase format. The geodatabase format is useful because data within it can be easily queried and manipulated by the user, and because spatial data can be visualized using ArcMap.

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8. Modification of cross section geometry was found to be the most efficient way of correcting inadequacies in floodplain mapping. Cove areas could be mapped by the extension of existing cross sections and/or the addition of new cross sections. River sinuosity problems could be corrected by the clipping and toeing of existing cross sections on the inside of river bends.

9. ESRI's new Model Builder system proved effective for generating floodplain maps and damage reports, and for managing and archiving these results.

10. Use of a standardized data model greatly reduced the complexity of the Model Builder routines. This resulted in simple GUI interfaces that require only minimal amounts of user input in order to perform calculations.

6.3 FUTURE RESEARCH OPPORTUNITIES

This project has demonstrated the potential for further research in a number of areas. One issue that needs further exploration is how to handle large time series datasets within the GIS environment. Whether these datasets are stored directly in a geodatabase, or in some other format that is accessible by GIS, these data are necessary for performing hydrologic simulations, and thus for creating a hydrologic information system.

In the long term, the HMS IDM could be used for performing simulations as well as for storing model data. The IDM is a potential platform from which new HMS models could be created and from which existing models could be run and results visualized. To accomplish these goals, however, data transfer procedures and codes must be developed. An even more ambitious goal would be to modify the HMS program to run directly on the geodatabase instead of the text files and DSS files currently used.

The development of a more formal data model for the flood damage evaluation system could also be an important goal. This development would include a UML model,

and more standardized field names. If multiple organizations would agree to use a standardized data model for flood studies, then the results of these studies would be more comparable. Furthermore, programs like the Model Builder routines developed by this project, would be applicable to all organizations that use the same data model.

Further study of the advantages of using a spatially distributed system to determine flood damages could also be revealing. As discussed in Chapter 2, the National Research Council believes that a spatially distributed damage analysis could be an improvement over the traditional lumped model. A more thorough comparison of the two methods could potentially verify this recommendation.

6.4 OVER-ALL PROJECT SIGNIFICANCE

Although this project involved three different research goals: (1) an Arc Hydro data model, (2) a HMS interface data model, and (3) a GIS-based flood damage evaluation system; the underlying concepts are the same. This project involved GIS and standardized data models. Standardized data models provide a data format around which computational programs can be designed, and GIS provides an effective method for viewing and analyzing the spatial variation in the data. These are the reasons Arc Hydro was created, and these are the principles that guided this research. This project has verified, utilized, and expanded the potential of these underlying concepts.

Appendix A: "LCRA World" GIS Repository

ArcMap "LCRA World" data menu

Layer Name	Category	Type
Contour Mapping Extent	LCRA	Polygon
Councils of Government Txdot (24k)	Boundary/Administrative	Polygon
County Boundaries Txdot - Coast Lines (24k)	Boundary/Administrative	Polygon
County Boundaries Txdot (24k)	Boundary/Administrative	Polygon
DEM Hillshade 24k	Imagery	Image Catalog
DOQQs 1 meter	Imagery	Image Catalog
DOQQs 1 meter BW	Imagery	Image Catalog
Easements LCRA	LCRA	Polygon
Ecological Regions	Environment	Polygon
Electric Service Area	LCRA	Polygon
Golden Cheek Warbler Zone	Environment	Polygon
High Water Marks (December 1991)	Hydro	Point
High Water Marks (June 1997)	Hydro	Point
High Water Marks (Llano 2000)	Hydro	Point
High Water Marks (October 1998)	Hydro	Point

ver 2.0.1251

LCRA GIS Repository Layer List

Name
Aerial Mapping Extent This data set shows the extent of the contour data which was produced from the Riverfront aerial images by the Aerial Photography Reduction Company (ADR). The outline is defining the contract line.
Index Transmission Line Imagery This is a polygon index of Transmission Services Aerial imagery.
Aquifer Major This major aquifers of Texas are delineated according to the Hydrologic Monitoring Section of the Texas Water Development Board. The map originates from 1:250,000 Geology maps of Texas published by the Bureau of Economic.
Aquifer Minor This major aquifers of Texas are delineated according to the Hydrologic Monitoring Section of the Texas Water Development Board. The map originates from 1:250,000 Geology maps of Texas published by the Bureau of Economic.
Parcels - Austin County Austin County Parcels from The Austin Central Appraisal District..
Parcels - Bastrop County
Black-capped Vireo Zone A habitat assessment for the Black-Capped Vireo was conducted by PBS&J as part of an Environmental Impact Statement conducted for the Northern Hays County Service Area of the LCRA.
Parcels - Burnet County The dataset was created in congruence with the Phase I Mapping Project of the upper river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created from a combination of digitizing final tax plats and Microstation line data from the Burnet County Appraisal District (BCAD). The Polygons were attributed with a seventeen (17) digit Parcel ID number (PID). that references a Tax Reference number or Tax Rnumber. The scale of the microstation data was recieved in 1:200 and 1:400 formats. The final tax plats varied from 1:50 to 1:200 foot scales. Contact the Burnet County Appraisal District for Dates concerning their data.
Parcels – Caldwell County

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CAPCO Imagery 2002 REQUIRED: A brief narrative summary of the data set.

Census Block Groups ESRI (100k) U.S. Block Groups represents the Census block groups of United States.

Census Tracts ESRI (100k) U.S. Tracts represents the U.S. Census tracts of the United States.

Texas City Boundaries The city limits were selected from the TNRIS.

Texas City Points The GNIS contains locative information about almost 2 million physical and cultural features located throughout the US. TX_GNIS contains a clipped out segment of these names for Texas.Texas city points were obtained from this data.

Parcels - Colorado County The dataset was created in congruence with the Phase II Mapping Project of the lower river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created from a combination of digitizing hard copy maps from Colorado County Appraisal District (CCAD). The Polygons were attributed with a thirteen (13) digit Parcel ID number (PID). that references a Tax Reference number or Tax Rnumber. The Hard copy maps are 1978 Soil Conservation Service aerials with parcels hand drawn on the photos.

Parcels - Comal County

US 108th Congressional Districts ESRI (100k) U.S. 108th Congressional Districts represents an interim version of the political boundaries for the U.S. 108th Congressional Districts. The U.S. Census Bureau will release the official 108th Congressional District boundaries later in 2003.

Contour Mapping Extent This data set shows the extent of the contour data which was produced from the Riverfront aerial images by the Aerial Photography Reduction Company (ADR). The outline is defining the contract line.

DOQQs 1 meter REQUIRED: A brief narrative summary of the data set.

USGS Quads (24k) REQUIRED: A brief narrative summary of the data set.

Ecological Regions Coverage of the Ecoregions are based on perceived patterns of a combination of causal and integrative factors including land use, land surface form, potential natural vegetation, and soils (Omernik, 1987).

Electric Service Area The LCRA service area is an area that is determined by the area of 11 Electric Cooperatives-. LCRA Wholesale customers. The coverage contains 33 cities and the areas that are certified to other companies inside the LCRA electric service area.

Colorado River EPA (100k) This coverage represents the Colorado River located in the State of Texas.

Lakes EPA (100k) The lakes data was clipped from reg12_83, a rf3 file from the EPA. 1:100,000. This coverage represents lakes located in the State of Texas within the LCRA Service Area.

Parcels - Fayette County The dataset was created in congruence with the Phase II Mapping Project of the lower river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created from a combination of digitizing hard copy maps from Fayette County Appraisal District (FCAD). The Polygons were attributed with a 6 (6) digit Parcel ID number (PID). This references a Tax Reference number or Tax Rnumber on the Appraisal database. The Hard copy maps appear to be Oil and gas maps with parcels and the owners name on the maps.

Golden Cheek Warbler Zone A habitat assessment for the Golden-Cheeked Warbler was conducted by PBS&J as part of an Environmental Impact Statement conducted for the Northern Hays County Service Area of the LCRA.

LCRA Harn Network This coverage was developed to aid in mapping all LCRA Survey Projects to a consistent GPS derived coordinate base. This GPS network is constrained to 12 NGS A&B order GPS Points and over 100 NGS Benchmarks. This network will support mapping accuracies of +- 2cm horizontal positioning and +- 5cm vertical positioning. This sub HARN network cover most of LCRA's Central Texas Service Area.

High Water Marks (June 1997) These points were surveyed by LCRA. They are high water and debris marks on the Llano and Colorado Rivers as a result of the flooding of the communities along the Llano and Colorado rivers in June of 1997.

High Water Marks (Llano 2000) These points were surveyed by LCRA. They are high water and debris marks on the Colorado River as a result of the flooding of the communities along the Colorado River in 2000.

High Water Marks (October 1998) These points were surveyed by LCRA. They are high water and debris marks on the Colorado Rivers as a result of the flooding of the communities along the Colorado river in October 1998.

High Water Marks (Walnut Creek 1995) These points were surveyed by Terry Nygaard with the Surveying and Mapping Department (LCRA). They are high water and debris marks in the Walnut Creek area as a result from the flooding of the community of Sandy Harbor in 1995.

High Water Marks (December 1991) HIGH WATER MARKS CHRISTMAS FLOOD OF 1991 NOTE 1 : Files LCOL013A and LCOL014A have **TBM's set to locate high water marks by Sean Maijala or George Fears. NOTE 2 : The file names shown are Surveying & Mapping project files and should be used when requesting Mapping. NOTE 3 : Coordinates shown are NAD 83 Texas Central Zone (4203) State Plane coordinates in US Survey Feet. NOTE 4 : Vertical Datum is NGVD 29 NOTE 5 : Coordinates derived using Real Time DGPS (+-1 Meter)

Hydro GDT Arcs REQUIRED: A brief narrative summary of the data set.

Hydro GDT Polys REQUIRED: A brief narrative summary of the data set.

Hydro Arcs Txdot (24k) Stream and shoreline arcs within the state of Texas. Lines digitized by Texas Dept. of Transportation (TxDOT) and extracted from county map series files by Texas General Land Office (GLO) personnel. Attribute values added by GLO personnel.

Hydro Polys Txdot (24k) Stream and shoreline arcs within the state of Texas. Lines digitized by Texas Dept. of Transportation (TxDOT) and extracted from county map series files by Texas General Land Office (GLO) personnel. Attribute values added by GLO personnel.

Hydromet Stations LCRA The Hydromet data is a point coverage of gauge stations within the Colorado River watershed. Hydromet allows remote interrogation of a networked system of twent-one self-reporting rainfall gages, twenty-one remotely monitored streamflow gages, and six reservoir elevation gages. Twenty of the streamflow gages also gather rainfall information, giving a total of forty-one rainfall sites. This system covers the Lower Colorado River, its three major and three minor tributaries, as well as the Highland Lakes. Hydromet allows each station to be polled both on a user-set interval, usually every hour, and independently at any other time. The real time data is logged and maintained on an on-line historical database for one year. This data is accessible for operations models, historical analyses or other needs. Data set was acquired from David Murdock.

Index DOQQ 1m (24k) This index is used to access the DOQQ images.

Index Quads USGS (24k) This file shows the position of the 7.5 minute USGS quads over Texas. 4376 quads cover the state.

Parcels - Kendall County Kendall County Parcel Information. Data Was Acquired from Kendall Central Appraisal District. Origin projection State plane South Central Zone Nad 83 feet.

Parcels - Kerr County Kerr County Appraisal District Parcel and Owner information.

LCRA Parks LCRA Parks is a composite layer created from a variety of sources. It primarily comes from the LIUP (LCRA parcels), but it has been adjusted according to the LCRA Parks Department information. The final product adequately displays the park boundaries and accurately corresponds with the Parks Department's non-spatial databases.

Parcels - Lee County A brief narrative summary of the data set. REQUIRED.

Parcels - Llano County The dataset was created in congruence with the Phase I Mapping Project of the upper river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created from a combination of digitizing final tax plats and Microstation line data from the LLano County Appraisal District (LCAD). The Polygons were attributed with a seventeen (16) digit Parcel ID number (PID). that references a Tax Reference number or Tax Rnumber. The final tax plats varied from 1:50 to 1:200 foot scales. Contact the Llano County Appraisal District for Dates concerning their data.

Parcels - Matagorda County The dataset was created in congruence with the Phase II Mapping Project of the lower river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created by acquiring hard copy maps from the Matagorda County Appraisal District. The CAD Hard copy maps contain linework andand parcel numbers for each parcel at a scale of 1" = 500' or 1" = 1000'.

Index Metcalfe Surveys A brief narrative summary of the data set. REQUIRED.

NHD Hydro Arcs (100k) The National Hydrography Dataset (NHD) is a feature-based database that interconnects and uniquely identifies the stream segments or reaches that comprise the nations surface water drainage system. It is based initially on the content of the U.S. Geological Survey 1:100,000-scale Digital Line Graph (DLG) hydrography data, integrated with reach-related information from the U.S. Environmental Protection Agency Reach File Version 3.0 (RF3). More specifically, it contains reach codes for networked features and isolated lakes, flow direction, names, stream level, and centerline representations for areal water bodies. Reaches are also defined to represent waterbodies and the approximate shorelines of the Great Lakes, the Atlantic and Pacific Oceans, and the Gulf of Mexico. The NHD also incorporates the National Spatial Data Infrastructure framework criteria set out by the Federal Geographic Data Committee.

NHD Hydro Polys (100k) The National Hydrography Dataset (NHD) is a feature-based database that interconnects and uniquely identifies the stream segments or reaches that comprise the nations surface water drainage system. It is based initially on the content of the U.S. Geological Survey 1:100,000-scale Digital Line Graph (DLG) hydrography data, integrated with reach-related information from the U.S. Environmental Protection Agency Reach File Version 3.0 (RF3). More specifically, it contains reach codes for networked features and isolated lakes, flow direction, names, stream level, and centerline representations for areal water bodies. Reaches are also defined to represent waterbodies and the approximate shorelines of the Great Lakes, the Atlantic and Pacific Oceans, and the Gulf of Mexico. The NHD also incorporates the National Spatial Data Infrastructure framework criteria set out by the Federal Geographic Data Committee.

Original Texas Land Surveys (24k) This dataset is the Railroad Commission's interpretation of the Original Texas Land Surveys boundaries and bay tracts. The dataset was derived from the Texas General Land Office (GLO) county maps, the GLO Abstract of Original Land Titles: Volumes and Supplements, and the GLO maps of State-Owned Submerged Lands of the Texas Gulf Coast (bay tracts). The GLO county maps, showing the boundaries of the original land grants of the State of Texas, were compiled and drawn by General Land Office

draftsmen. This dataset is a digital interpretation of the geographic placement of the original land grants and bay area tracts depicted on these GLO maps and is not a legal survey product.

Parks GDT REQUIRED: A brief narrative summary of the data set.

Phone Area Codes ESRI (100k) U.S. Telephone Area Code Boundaries represents the telephone area codes for United States. They are also known as Numbering Plan Areas (NPA).

Railroads GDT REQUIRED: A brief narrative summary of the data set.

Railroads Txdot (24k) The Rail Network is a comprehensive database of the nation's railway system at the 1:100,000 scale.

Recreational Areas GDT REQUIRED: A brief narrative summary of the data set.

Riverfront Bridges (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics (bridge outlines) for all visible structures.

Riverfront Buildings (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics (building outlines) for all visible structures.

Riverfront Contours REQUIRED: A brief narrative summary of the data set.

Riverfront Docks (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics (Dock & Pier outlines) for all visible structures.

Riverfront Drainage (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics (Linear drainage, e.g. creeks & streams) for all visible features.

Riverfront Imagery REQUIRED: A brief narrative summary of the data set.

Riverfront Index A brief narrative summary of the data set. REQUIRED.

Riverfront Roads (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics (roads & centerlines) for all visible features.

Riverfront Spots (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics Spot Elevations).

Riverfront Waterbodies (2400) The scope of the project is to map the Colorado river corridor from San Saba County to Matagorda County Texas. Contour mapping includes: 1) Obtaining aerial photographs (Flight Scale: 1"=1400' and mapping scale is 1" = 200') of the Colorado River (2-19-98 thru 2-19-99); 2) In non-urban areas, preparing digital mapping to national map accuracy standards (4-foot contours up to one contour beyond the 500-year flood zone) and interpolating this to 2 - foot contours; 3) In five urban areas prepare digital mapping to national map accuracy standards (2-foot contours interpolated to 1-foot); 4) Producing a digital elevation model for the area extending 1,000 feet beyond the 500-year flood zone; Preparing digital orthophotography for the entire area; 6) Preparing planimetrics Water Body outlines) for all visible features.

Roads ESRI - Interstate Hwys U.S. Major Roads represents interstate, U.S. and state highways, major streets, and other major thoroughfares within the United States.

Roads ESRI - State and Minor Hwys U.S. Major Roads represents interstate, U.S. and state highways, major streets, and other major thoroughfares within the United States.

Roads ESRI - US Hwys U.S. Major Roads represents interstate, U.S. and state highways, major streets, and other major thoroughfares within the United States.

Roads GDT - Statewide REQUIRED: A brief narrative summary of the data set.

Roads 911 - New World Systems REQUIRED: A brief narrative summary of the data set.

Texas School District Boundaries 2003 Texas public school district boundaries.

Texas Public School Locations 2003 All public schools in Texas

Stratmap Cities (24k) The statewide Texas boundary dataset is one component of the Texas Strategic Mapping Program (StratMap). The StratMap program developed seven digital base map, or " Framework," layers for Texas. StratMap is managed by the Texas Natural Resources Information System (TNRIS), a division of the Texas Water Development Board (TWDB). All data produced through StratMap are available in the public domain. The StratMap boundary dataset produced files corresponding to multi-county councils of government across Texas as well as a statewide dataset. Each boundary file has five themes including state, county, city, parks, and other (i.e. federal lands, landmarks, country clubs). The data sources for each council of government coverage vary but could include digital orthophoto quads (DOQs), USGS digital raster graphics (DRGs), Texas Department of Transportation data, and local data from the council of governments or its component governments. The attribute coding scheme is designed to accommodate several basic cartographic data categories such as feature type, feature name, jurisdiction entity, data source used in feature collection, data source date and revision date(s) if applicable.

Stratmap COGs (24k) The statewide Texas boundary dataset is one component of the Texas Strategic Mapping Program (StratMap). The StratMap program developed seven digital base map, or " Framework," layers for Texas. StratMap is managed by the Texas Natural Resources Information System (TNRIS), a division of the Texas Water Development Board (TWDB). All data produced through StratMap are available in the public domain. The StratMap boundary dataset produced files corresponding to multi-county councils of government across Texas as well as a statewide dataset. Each boundary file has five themes including state, county, city, parks, and other (i.e. federal lands, landmarks, country clubs). The data sources for each council of government coverage vary but could include digital orthophoto quads (DOQs), USGS digital raster graphics (DRGs), Texas Department of Transportation data, and local data from the council of governments or its component governments. The attribute coding scheme is designed to accommodate several basic cartographic data categories such as feature type, feature name, jurisdiction entity, data source used in feature collection, data source date and revision date(s) if applicable.

Stratmap Counties (24k) The statewide Texas boundary dataset is one component of the Texas Strategic Mapping Program (StratMap). The StratMap program developed seven digital base map, or " Framework," layers for Texas. StratMap is managed by the Texas Natural Resources Information System (TNRIS), a division of the Texas Water Development Board (TWDB). All data produced through StratMap are available in the public domain. The StratMap boundary dataset produced files corresponding to multi-county councils of government across Texas as well as a statewide dataset. Each boundary file has five themes including state, county, city, parks, and other (i.e. federal lands, landmarks, country clubs). The data sources for each council of government coverage vary but could include digital orthophoto quads (DOQs), USGS digital raster graphics (DRGs), Texas Department of Transportation data, and local data from the council of governments or its component governments. The attribute coding scheme is designed to accommodate several basic cartographic data categories such as feature type, feature name, jurisdiction entity, data source used in feature collection, data source date and revision date(s) if applicable.

Stratmap Other Boundaries (24k) The statewide Texas boundary dataset is one component of the Texas Strategic Mapping Program (StratMap). The StratMap program developed seven digital base map, or " Framework," layers for Texas. StratMap is managed by the Texas Natural Resources Information System (TNRIS), a division of the Texas Water Development Board (TWDB). All data produced through StratMap are available in the public domain. The StratMap boundary dataset produced files corresponding to multi-county councils of government across Texas as well as a statewide dataset. Each boundary file has five themes including state, county, city, parks, and other (i.e. federal lands, landmarks, country clubs). The data sources for each council of government coverage vary but could include digital orthophoto quads (DOQs), USGS digital raster graphics (DRGs), Texas Department of Transportation data, and local data from the council of

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governments or its component governments. The attribute coding scheme is designed to accommodate several basic cartographic data categories such as feature type, feature name, jurisdiction entity, data source used in feature collection, data source date and revision date(s) if applicable.

Stratmap Parks (24k) The statewide Texas boundary dataset is one component of the Texas Strategic Mapping Program (StratMap). The StratMap program developed seven digital base map, or " Framework," layers for Texas. StratMap is managed by the Texas Natural Resources Information System (TNRIS), a division of the Texas Water Development Board (TWDB). All data produced through StratMap are available in the public domain. The StratMap boundary dataset produced files corresponding to multi-county councils of government across Texas as well as a statewide dataset. Each boundary file has five themes including state, county, city, parks, and other (i.e. federal lands, landmarks, country clubs). The data sources for each council of government coverage vary but could include digital orthophoto quads (DOQs), USGS digital raster graphics (DRGs), Texas Department of Transportation data, and local data from the council of governments or its component governments. The attribute coding scheme is designed to accommodate several basic cartographic data categories such as feature type, feature name, jurisdiction entity, data source used in feature collection, data source date and revision date(s) if applicable.

Stream Segments Stream segments of the Colorado River Basin. The EPA developed the stream identification numbers and boundaries.

Substations LCRA This coverage contains LCRA facilities associated with the Department of Tensco, and all intrests in Cooperative substaions in the LCRA Electric Service area. The point coverage contains Substations, Switches, Taps. This data is of Current data and Does not reflect Historical facilities that no longer exist, no longer have metering points, or materials present in the facility.

Substations LCRA Owned This coverage contains LCRA Substation properties in the LCRA Electric Service area.

Hospitals TDH Hospital Locations in Texas

Transmission Easements LCRA This data set includes those electric transmission line easements owned by Transmission Services Corporation.

Transmission Easements Amendments LCRA This data set includes those electric transmission line amendments owned by Transmission Services Corporation.

Transmission Lines LCRA This dataset represents those electric transmission lines considered part of the LCRA electric transmission system. Included in this data set are both LCRA owned/operated lines and Coop owned/operated lines.

Transmission - T136 REQUIRED: A brief narrative summary of the data set.

Transmission - T146 REQUIRED: A brief narrative summary of the data set.

Transmission - T150 REQUIRED: A brief narrative summary of the data set.

Transmission - T201, T205, T233 REQUIRED: A brief narrative summary of the data set.

Transmission - T266 REQUIRED: A brief narrative summary of the data set.

Transmission - T270 REQUIRED: A brief narrative summary of the data set.

Transmission - T315 REQUIRED: A brief narrative summary of the data set.

Transmission - T358 REQUIRED: A brief narrative summary of the data set.

Transmission - T359 REQUIRED: A brief narrative summary of the data set.

Transmission - T360 REQUIRED: A brief narrative summary of the data set.

Transmission - T374 REQUIRED: A brief narrative summary of the data set.

Transmission - T381 REQUIRED: A brief narrative summary of the data set.

Transmission - T391 REQUIRED: A brief narrative summary of the data set.

Transmission - T392 REQUIRED: A brief narrative summary of the data set.

Transmission - T400 REQUIRED: A brief narrative summary of the data set.

Transmission - T413 REQUIRED: A brief narrative summary of the data set.

Transmission - T438 REQUIRED: A brief narrative summary of the data set.

Transmission - T459 REQUIRED: A brief narrative summary of the data set.

Parcels - Travis County The dataset was created in congruence with the Phase I Mapping Project of the upper river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created from 1:100 and 1:400 raster based Travis County Appraisal District tax maps. Heads up digitizing was used to capture the parcel boundries.

Texas House Districts 2002 Texas House districts for the year 2002 elections, as ordered by US District Court for the Eastern District of Texas

Texas Senate Districts Texas Senate districts for the year 2002 elections, as adopted by the Texas Legislative Redistricting Board

County Boundaries Txdot - Coast Lines (24k) Source data was obtained from the Texas Department of Transportation and processed into a state-wide coverage by TNRIS.

Councils of Government Txdot (24k) Texas counties digitized from Texas department of Transportation

county highway maps. These include roads, rivers, and city boundaries. Originally digitized from USGS quads and continuously updated. Coverages do not include features such as contours, fence lines, small creeks, electrical lines, and pipelines. Number of files range fron 4 to 25+ per county. Amount of storage needed per county is 150 kb to 30 mb.

County Boundaries Txdot (24k) Texas counties digitized from Texas department of Transportation county highway maps. These include roads, rivers, and city boundaries. Originally digitized from USGS quads and continuously updated. Coverages do not include features such as contours, fence lines, small creeks, electrical lines, and pipelines. Number of files range fron 4 to 25+ per county. Amount of storage needed per county is 150 kb to 30 mb.

LCRA Service Area Txdot (24k) Texas counties digitized from Texas department of Transportation county highway maps. These include roads, rivers, and city boundaries. Originally digitized from USGS quads and continuously updated. Coverages do not include features such as contours, fence lines, small creeks, electrical lines, and pipelines. Number of files range fron 4 to 25+ per county. Amount of storage needed per county is 150 kb to 30 mb.

LCRA Statutory District Txdot (24k) Texas counties digitized from Texas department of Transportation county highway maps. These include roads, rivers, and city boundaries. Originally digitized from USGS quads and continuously updated. Coverages do not include features such as contours, fence lines, small creeks, electrical lines, and pipelines. Number of files range fron 4 to 25+ per county. Amount of storage needed per county is 150 kb to 30 mb.

State of Texas Txdot (24k) Texas counties digitized from Texas department of Transportation county highway maps. These include roads, rivers, and city boundaries. Originally digitized from USGS quads and continuously updated. Coverages do not include features such as contours, fence lines, small creeks, electrical lines, and pipelines. Number of files range fron 4 to 25+ per county. Amount of storage needed per county is 150 kb to 30 mb.

Parcels - Washington County Washington Central Appraisal District Parcels acquired from the Washington County IMS website connection clear.tamu.edu

Water Service Area LCRA (24k) This coverage represents the Lower Colorado River Authorities water service boundary at a resolution of 1:24,000. The boundary is a composite area described by the boundaries of the watershed that contributes inflow to the Colorado River below the intersection of Coleman, Brown and McCulloch counties, and the LCRA 10-County statutory district which include the counties of Blanco, Burnet, Llano, Travis, Bastrop, Fayette, Colorado,Wharton, San Saba and Matagorda. Within this boundary, the LCRA has the rights to control, store and preserve the waters of the Colorado River.

WTC Imagery The data set provides color aerial photography.

Watersheds - Colorado River Based on the USGS Hydrologic Unit Code maps prepared in conjunction with the U.S. Water Resources Council at a scale of 1:500,000. Subbasins, as defined by USGS, have been combined to create 11 subwatersheds within the Colorado River watershed. Watershed boundaries have been edited by EP Staff.

Watersheds - Sub - Colorado River Based on the USGS Hydrologic Unit Code maps prepared in conjunction with the U.S. Water Resources Council at a scale of 1:500,000. Subbasins, as defined by USGS, have been combined to create 11 subwatersheds within the Colorado River watershed. Watershed boundaries have been edited by EP Staff.
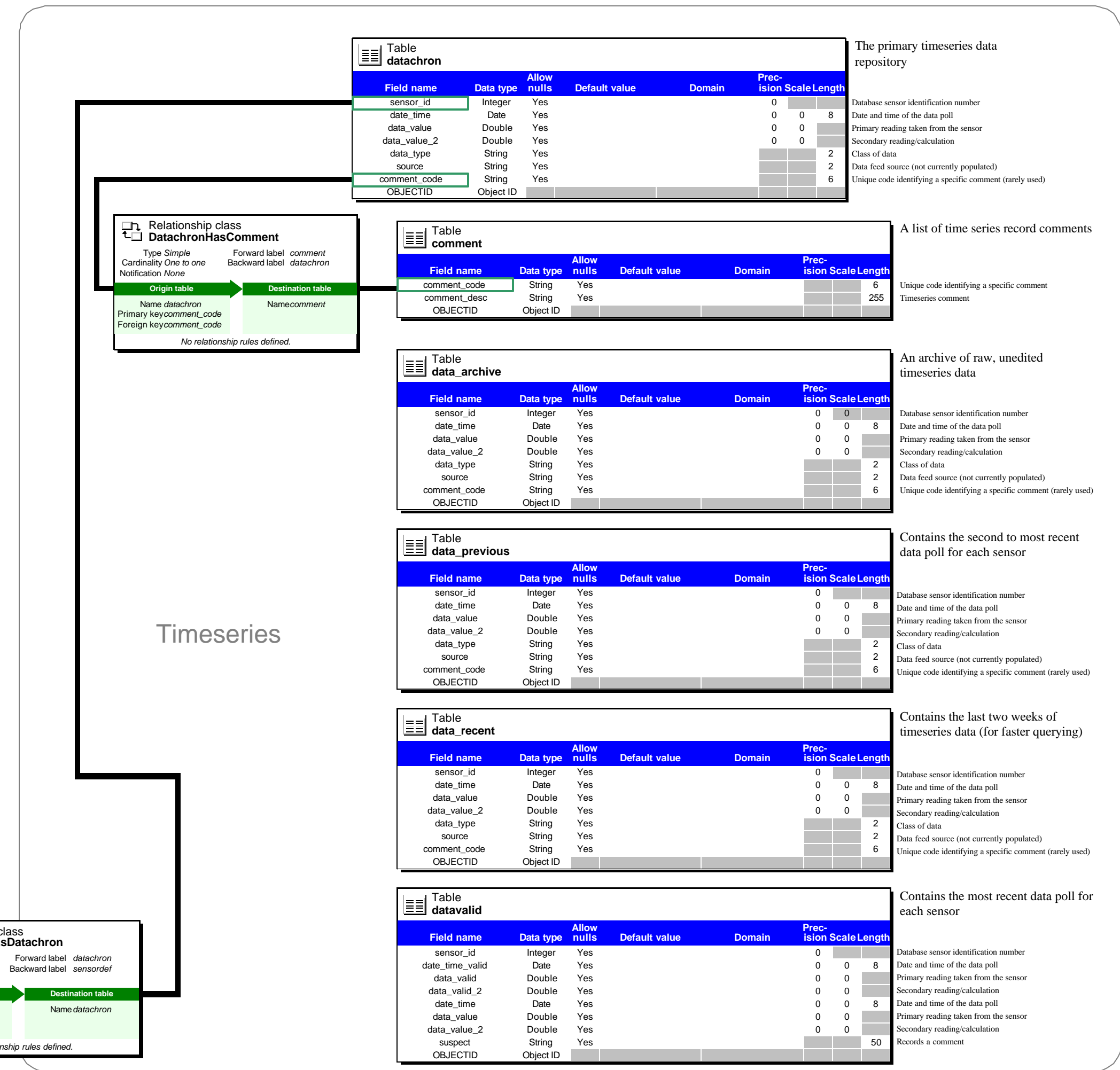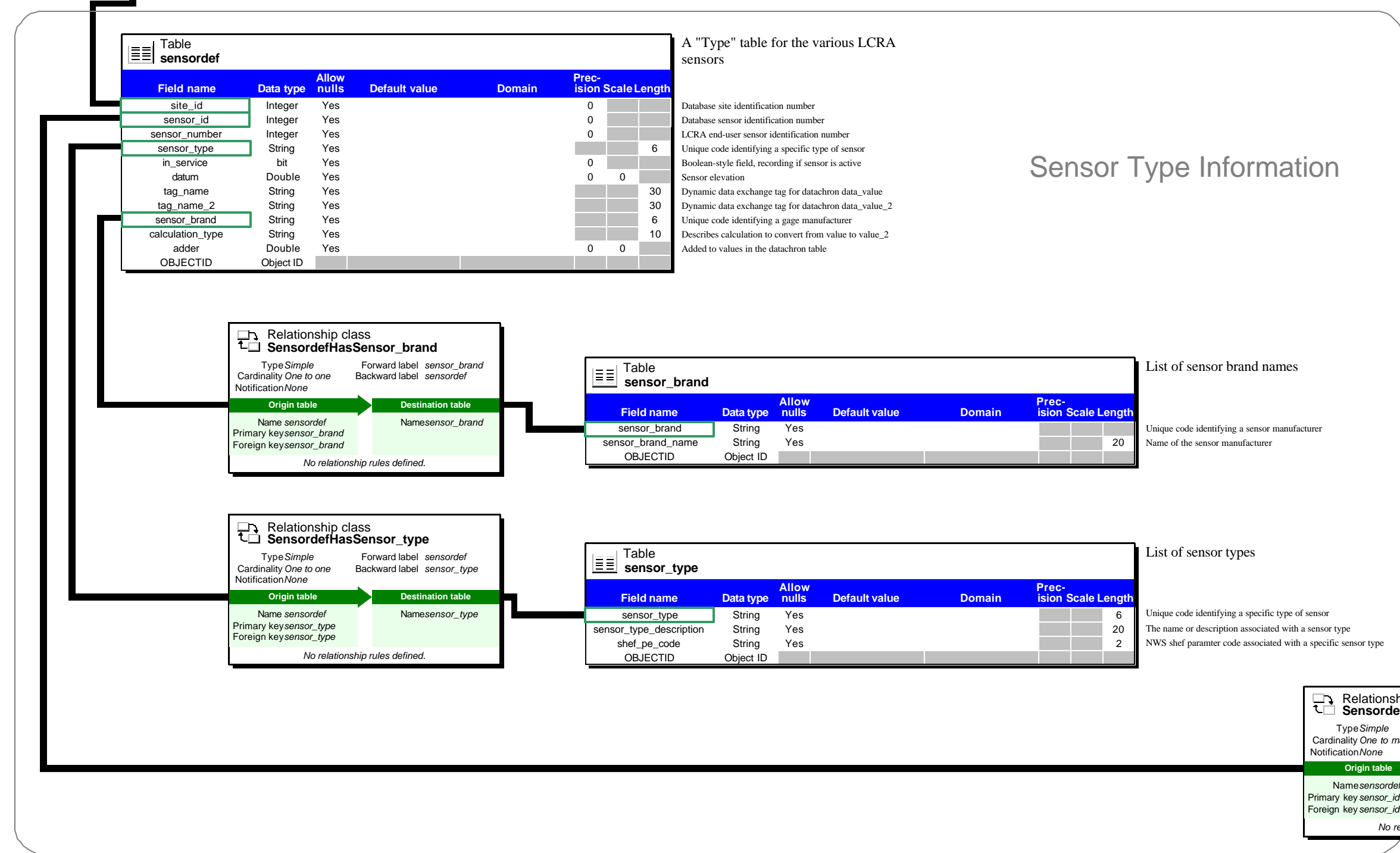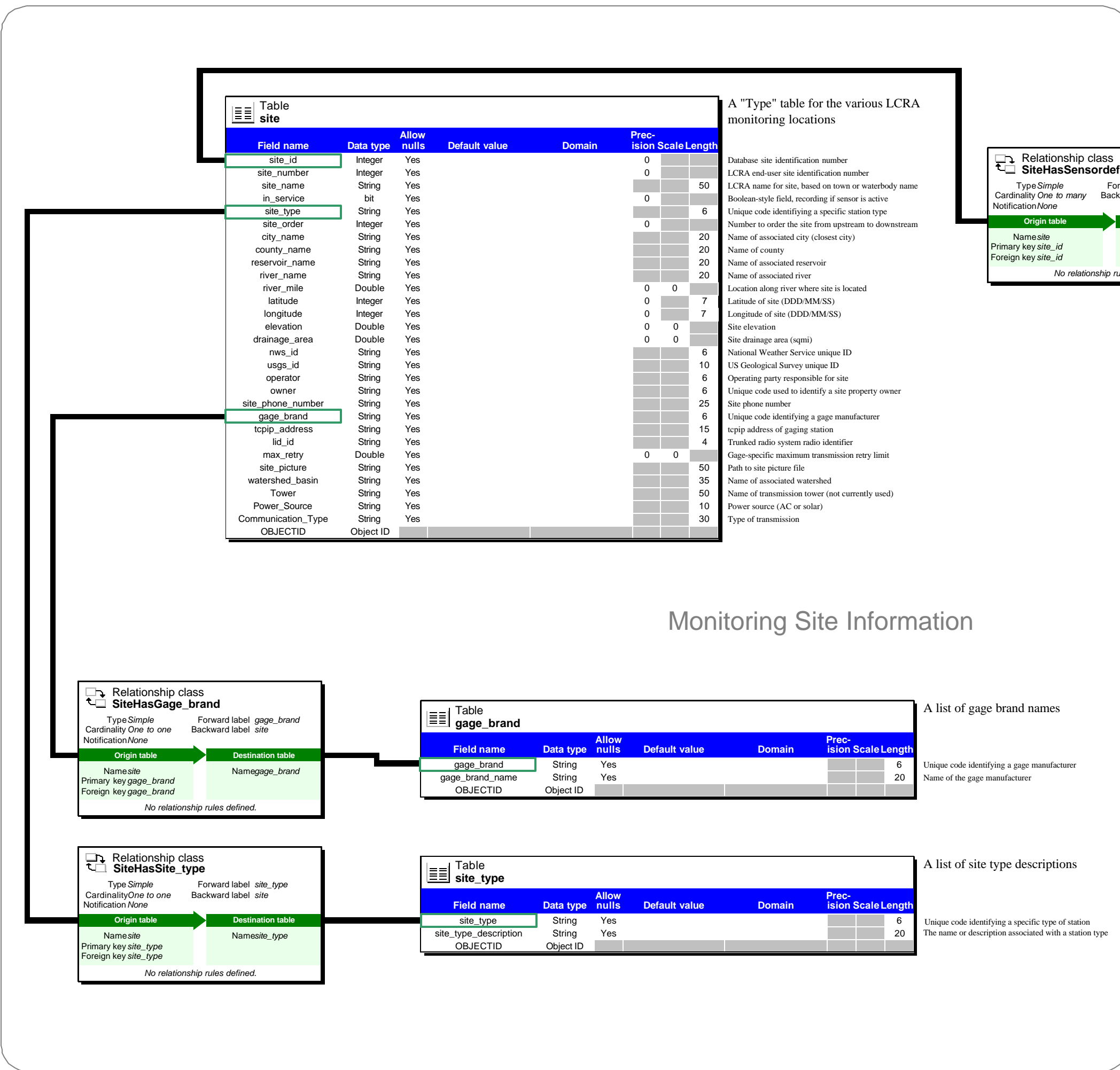
Parcels - Wharton County The dataset was created in congruence with the Phase II Mapping Project of the lower river basin by WaterCo within the Lower Colorado River Authority (LCRA). The Data was created from Microstation line and annotation data from the Whartoon County Appraisal District (WCAD). The Polygons were attributed with a six (6) digit Parcel ID number (PID). This references a Tax Reference number or Tax Rnumber. The scale of the microstation data was recieved in a unknown formats. Contact the Wharton County Appraisal District for Dates concerning their data.

Parcels - Williamson County Williamson County Parcels was obtained by The Appraisal District of Williamson County. The data was converted from Microstation files to An ArcGIS Coverage. Steps will be explained in the Process Step section of Data Quality.

Zipcode Boundaries ESRI (100k) U.S. ZIP Code Areas represents five-digit ZIP Code areas used by the U.S. Postal Service to deliver mail more effectively. The first digit of a five-digit ZIP Code divides the country into 10 large groups of states numbered from 0 in the Northeast to 9 in the far West. Within these areas, each state is divided into an average of 10 smaller geographical areas, identified by the 2nd and 3rd digits. These digits, in conjunction with the first digit, represent a sectional center facility or a mail processing facility area. The 4th and 5th digits identify a post office, station, branch or local delivery area.
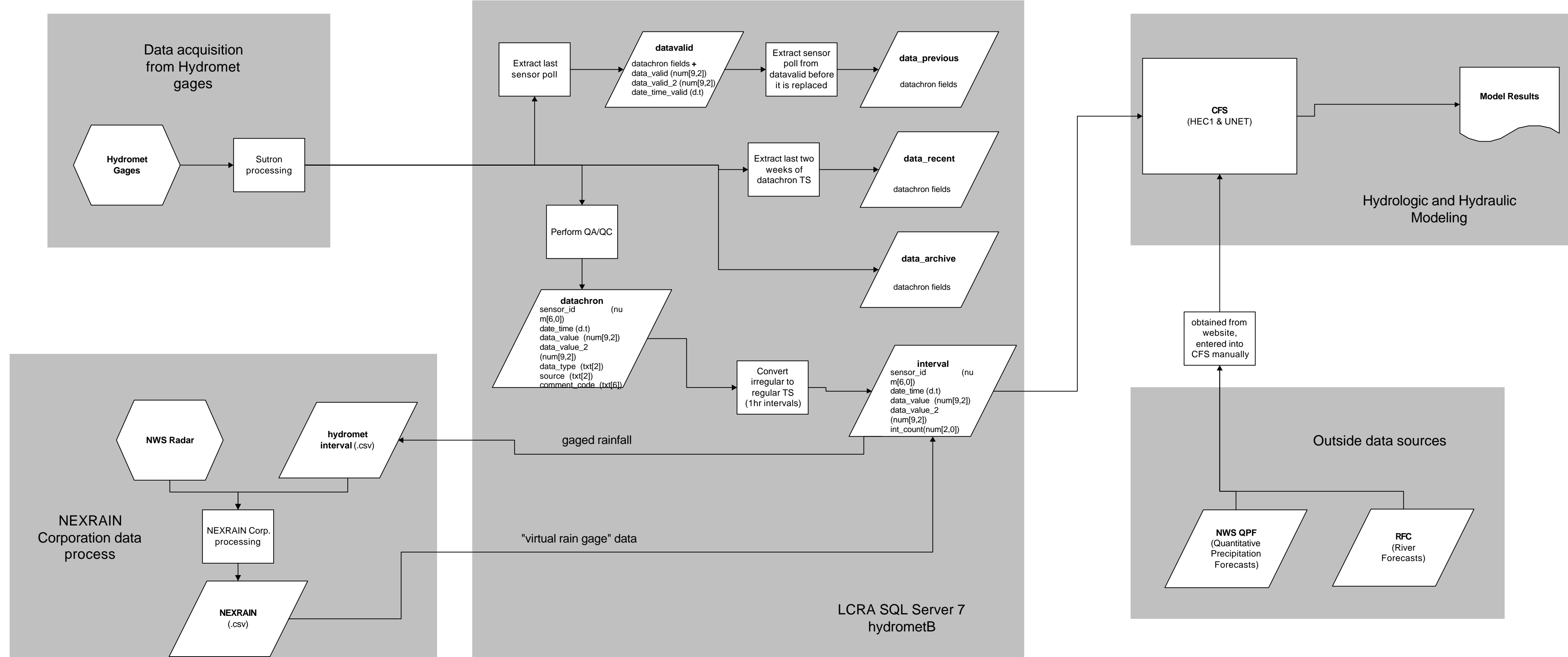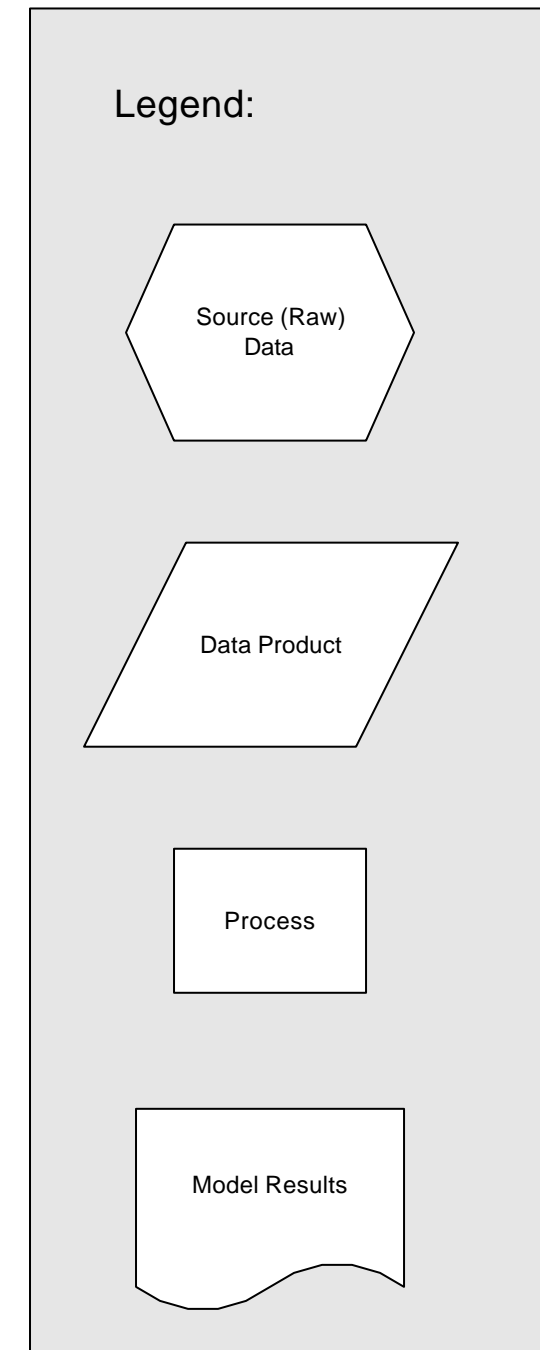
Appendix B: LCRA Hydromet Database Diagram

Primary Tables of the LCRA Hydromet Database Structure

Appendix C: LCRA Hydromet Flow Diagram

LCRA Hydromet Flow Diagram

Legend:

Source (Raw) Data

Data Product

Process

Model Results

Data acquisition from Hydromet gages

Hydromet Gages

Sutron processing

LCRA SQL Server 7 hydrometB

Extract last sensor poll

datavalid
datachron fields +
data_valid (num[9,2])
data_valid_2 (num[9,2])
date_time_valid (d.t)

Extract sensor poll from datavalid before it is replaced

data_previous
datachron fields

Extract last two weeks of datachron TS

data_recent
datachron fields

Perform QA/QC

data_archive
datachron fields

datachron
sensor_id   (nu
m[6,0])
date_time (d.t)
data_value (num[9,2])
data_value_2
(num[9,2])
data_type (txt[2])
source (txt[2])
comment_code (txt[6])

Convert irregular to regular TS (1hr intervals)

interval   (nu
sensor_id
m[6,0])
date_time (d.t)
data_value (num[9,2])
data_value_2
(num[9,2])
int_count(num[2,0])

NEXRAIN Corporation data process.

NWS Radar

hydromet interval (.csv)

NEXRAIN Corp. processing

NEXRAIN
(.csv)

"virtual rain gage" data

gaged rainfall

Hydrologic and Hydraulic Modeling

CFS
(HEC1 & UNET)

Model Results

obtained from website, entered into CFS manually

Outside data sources

NWS QPF
(Quantitative Precipitation Forecasts)

RFC
(River Forecasts)

Notes:

Table definitions:

datachron -- the primary data storage table
datavalid and data_previous -- stores the most recent (and second most recent) data polls of the hydromet system
interval -- stores data that has been adjusted to regular, 1 hour intervals, for use in modelling
data_recent -- stores the last two weeks of data in a smaller table, allowing for faster data querying
data_archive -- back-up of raw data (no QA/QC performed)

Associated tables:

The hydromet timeseries tables are related to a series of TSType-style tables , as shown in the graphic below:

datachron
primary timeseries storage table

sensor_id   (num[
6,0])
date_time (d.t)
data_value (num[9,2])
data_value_2 (num[9,2])
data_type (txt[2])
source (txt[2])
comment_code (txt[6])

sensordef
describes the monitoring instrument that took the reading

sensor_id   (num[
6,0])
site_id (num[8,0])
sensor_number(num[8,0])
sensor_type (txt[6])
in_service (txt[30])
tag_name (txt[30])
tag_name_2 (txt[30])
sensor_brand (txt[6])

site
describes the monitoring location

site_id (num[8,0])
site_number (num[8,0])
site_name (txt[50])
site_name_abbr (txt[30])
in_service (bit)
site_type (txt[6])
site_order (num[4,0])
city_name (txt[20])
county_name (txt[20])
reservoir_name (txt[20])
river_name (txt[20])
river_mile (num[6,2])
latitude (num[7,0])
longitude (num[7,0])
elevation (num[6,2])
drainage_area (num[7,2])
nws_id (txt[6])
usgs_id (txt[10])
operator (txt[6])
owner (txt[6])
site_phone_number (txt[25])
gage_brand (txt[6])
tcpip_address (txt[15])
lid_id (txt[4])
max_retry (num[2,0])
site_picture (txt[50])

comment_code is related to a "comment" table that gives long (255 character) descriptions.

sensor_id is related to extensive "quality_limits", "flood_level", and "alarm limits" tables.

sensor_type and sensor_brand are related to a "sensor_type" and "sensor_brand" table, which give long (20 character) descriptions.

gage_brand and site_type are related to a "gage_brand" and "site_type" table, which give long (20 character) descriptions.

owner is related to an extensive "site _owner" table

Appendix D: LCRA Water Quality Database Diagram

LCRA/TCEQ Water Quality Database Structure

Bi-Monthly Water Quality Sampling Data
taken at designated monitoring locations throughout the LC River Basin

Table — Station

Information about the locations where sampling events occur

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
Basin_ID	String	Yes					2	Unique identifier for basin in which site is located
Station_ID	String	Yes					5	Unique identifier for station
Station_Num	String	Yes					9	Unique identifier based on segment and station sequence
USGS_Gage	String	Yes					8	Unique identifier assigned by the USGS
ShortDescrip	String	Yes					30	Text describing the site's location
LongDescrip	String	Yes					135	Text describing the site's location
EPA_Type1	String	Yes					6	Code corresponding to the type of water feature the site is on
EPA_Type2	String	Yes					6	Code corresponding to the water conditions at the site
County	String	Yes					20	Full name of county in which site is located
County_ID	String	Yes					3	Code for the county
Segment_ID	String	Yes					4	Code assigned to a classified stream segment
Stream	String	Yes					4	Code assigned to the site, placing it in sequence with other sites
Region	String	Yes					2	Code corresponding to the TCEQ region in which the site is located
Latitude	Double	Yes			0	0		Latitude of sampling site
Longitude	Double	Yes			0	0		Longitude of sampling site
HUC	String	Yes					8	Hydrologic Unit Code assigned by the USGS
On_Segment	String	Yes					1	Indicates whether or not the site is located on a segment
OBJECTID	Object ID							

Table — Results

Water quality data obtained from a sampling event

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
Tag_ID	String	Yes					7	Link between Event and Results tables
EndDate	String	Yes					10	The date the sample was collected (MM/DD/YYYY)
StoretCode	String	Yes					5	A 5-digit code identifying the type of measurement
Gtlt	String	Yes					1	">" or "<" depending on whether the value is above or below detection limits
Value	String	Yes					8	Value of measurement (in units specified by the Storet table)
OBJECTID	Object ID							

Relationship class — EventHasResults

Type *Simple*
Cardinality *One to many*
Notification *None*
Forward label *Results*
Backward label *Event*

Origin table	Destination table
Name *Event*	Name *Results*
Primary key *Tag_ID*	
Foreign key *Tag_ID*	

No relationship rules defined.

Relationship class — StoretHasResults

Type *Simple*
Cardinality *One to many*
Notification *None*
Forward label *Results*
Backward label *Storet*

Origin table	Destination table
Name *Storet*	Name *Results*
Primary key *StoretCode*	
Foreign key *StoretCode*	

No relationship rules defined.

Table — Event

Conditions under which a sampling event was conducted

Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
Tag_ID	String	Yes					7	Link between Event and Results tables
Station	String	Yes					9	Combination of Station_ID and sequence of a site within a segment
Station_ID	String	Yes					5	Unique identifier for station
EndDate	String	Yes					10	The date the sample was collected (MM/DD/YYYY)
EndTime	String	Yes					5	The time the sample was collected (HH:MM)
EndDepth	String	Yes					6	The depth (meters) at which the sample was collected
StartDate	String	Yes					10	Starting date (composite samples only)
StartTime	String	Yes					5	Starting time (composite samples only)
StartDepth	String	Yes					6	Starting depth (for composite samples only)
Category	String	Yes					1	Code corresponding to the type of composite sample taken
Calculatn	String	Yes					1	--no longer used, should be left blank--
Type	String	Yes					2	Code corresponding to the number of samples taken in a composite
Comment	String	Yes					135	A record of any observational data included with the sample
Source1	String	Yes					2	A TNRCC assigned code for the agency submitting the sample
Source2	String	Yes					2	An optional field that further identifies the sample
Program	String	Yes					2	An optional field that further identifies the sample
OBJECTID	Object ID							

Relationship class — StationHasEvent

Type *Simple*
Cardinality *One to many*
Notification *None*
Forward label *Event*
Backward label *Station*

Origin table	Destination table
Name *Station*	Name *Event*
Primary key *Station_ID*	
Foreign key *Station_ID*	

No relationship rules defined.

Table — Storet

Description of the water quality parameter measured, and the technique used to measure it
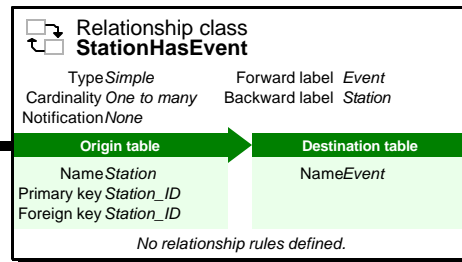
Field name	Data type	Allow nulls	Default value	Domain	Precision	Scale	Length	Description
StoretCode	String	Yes					5	A 5-digit code identifying the type of measurement
ShortDescrip1	String	Yes					8	Short descriptions including the water quality parameter measured, the units of measurement, and the measurement technique.
ShortDescrip2	String	Yes					8	
ShortDescrip3	String	Yes					8	
LongDescrip	String	Yes					50	Includes all of the metadata found in the 3 short descriptions
MinValue	Double	Yes			0	0		The lowest possible measurement
MaxValue	Double	Yes			0	0		The highest possible measurement
OBJECTID	Object ID							

Appendix E: Instructions – "Populating an Arc Hydro Dataset"

Populating The Arc Hydro data Model

Developed by: Daniel Obenour, CRWR; and Daniel Yates, LCRA

Created: November, 2002
Updated: January, 2003

Introduction:
  The following outline is an instruction set for preparing hydrological data for use in the Arc Hydro data model. The instructions assume that the user has a working knowledge of ArcGIS, Access, and Excel. It is recommended that you save backups of your database at various times throughout the data preparation process. Text appearing in italics is included to help explain and enhance the instructions.

1. Acquiring the Required Input Data.
   It is up to the designer to determine what data will be required for a given Arc Hydro project. River Reaches are required for all projects. Watersheds and Monitoring Points are generally included because they add functionality to the Arc Hydro model. Waterbodies (representing lakes and reservoirs) are not always required. Other data types may also be included at the designer's discretion, but are not discussed in detail in this paper. However, the procedures described in this paper are applicable to all data types.
   a. River Reaches – available for the U.S. through the National Hydrography Dataset (NHD) (http://nhd.usgs.gov).
   b. Waterbodies – available for the U.S. through the NHD.
   c. Watersheds – available through the NHD, other sources, and raster watershed delineation. Use watersheds that are of appropriate size for the basin being studied.
   d. Monitoring Points – available through the NHD or other agencies that monitor stream flow, water quality, rainfall, or water level.

e. Other Points of Interest – available though the NHD and other sources. May include structures, water users, water discharges, etc.
2. Preparing the Input Data.
    a. If your data for the River Reaches (item "a" of section 1) are in a number of separate shapefiles, open ArcMap and use the Geoprocessing Wizard to merge these files.
    b. Repeat step "a" for all of your other data types. When you finish you should have only one shapefile for each data type.
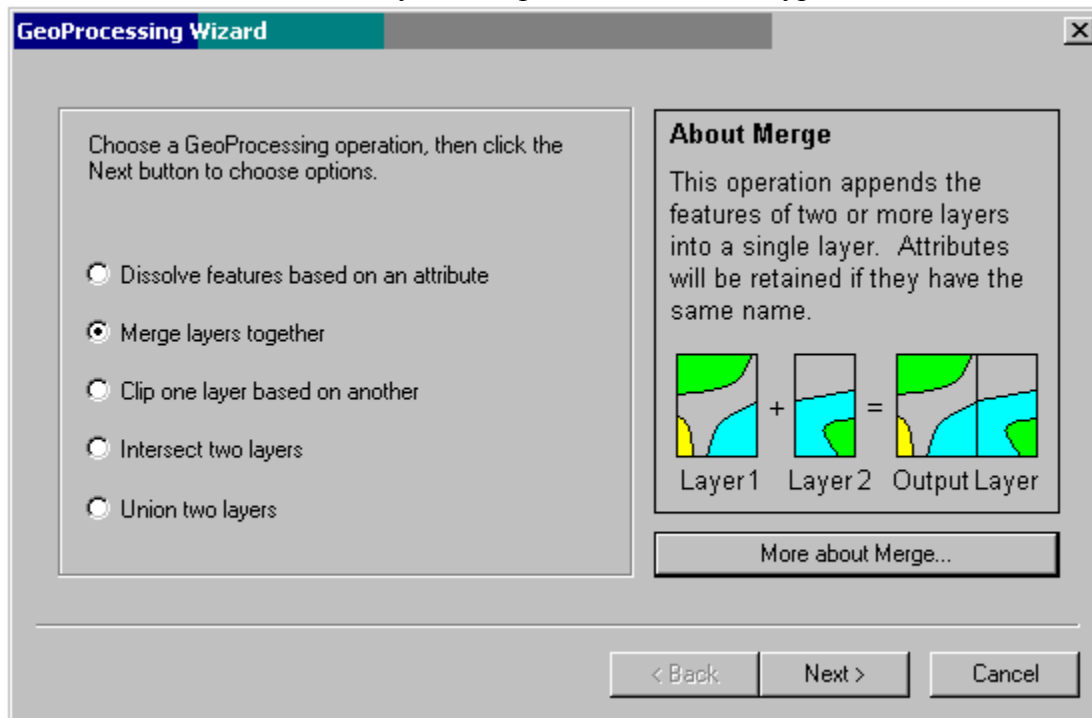

The Geoprocessing Wizard
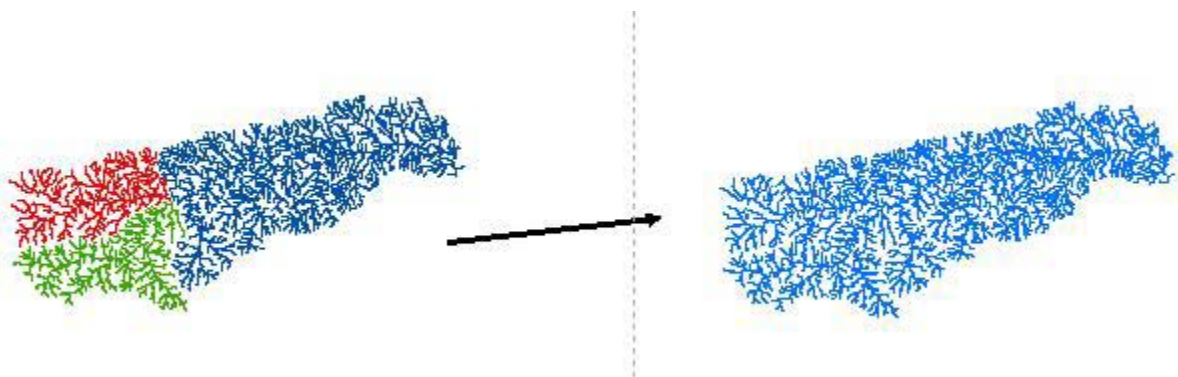
The merger of three different NHD HUC river files

3. Creating a Database.

a. In ArcCatalog, create a new personal geodatabase and assign it a name appropriate for your project.
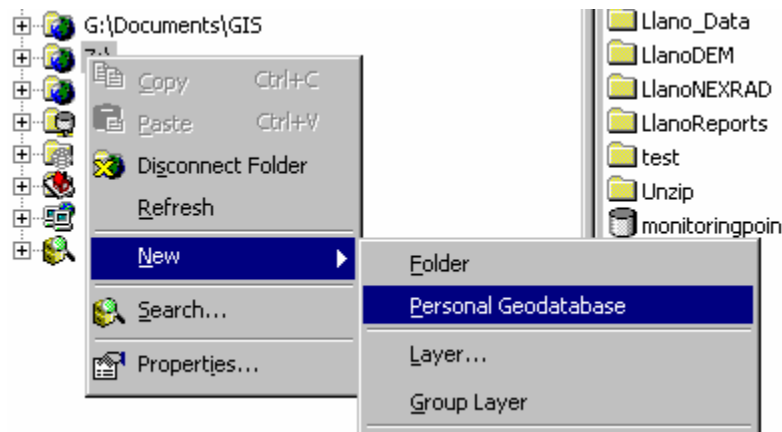
b. Launch ArcToolbox and convert your river reach shapefile into a projected coordinate system that is appropriate for your project. (Generally, use Albers Equal Area since it will maintain the accurate areas of watersheds.)
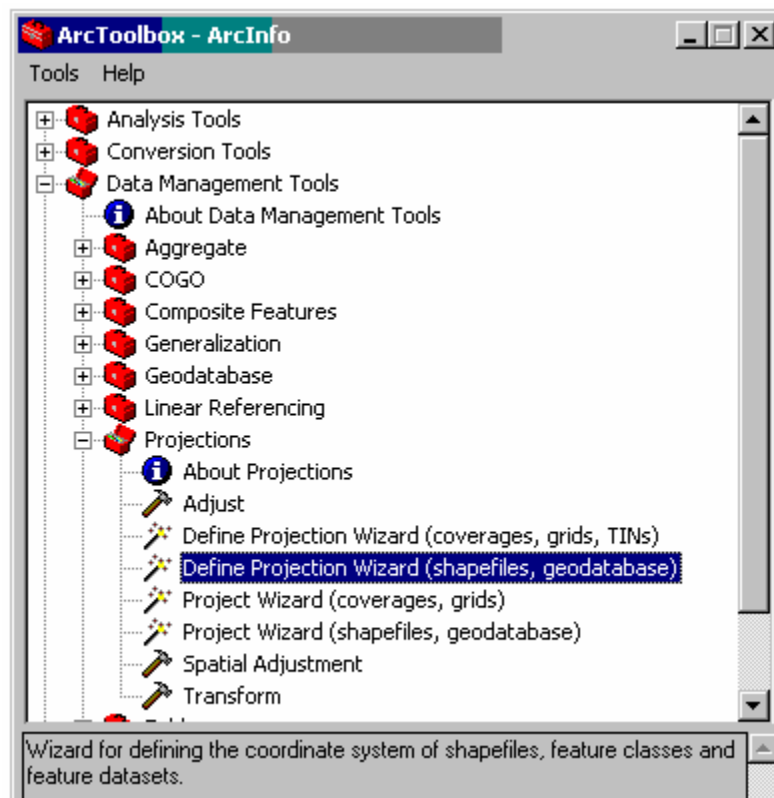
c. Export your river reach shapefile into your personal geodatabase and name it "HydroEdge". During this process, you will be required to create a feature dataset. Give it the name "ArcHydro". (Make sure to add the shapefile with the largest spatial extents first; the first shapefile imported sets the spatial extent for the entire feature dataset.)
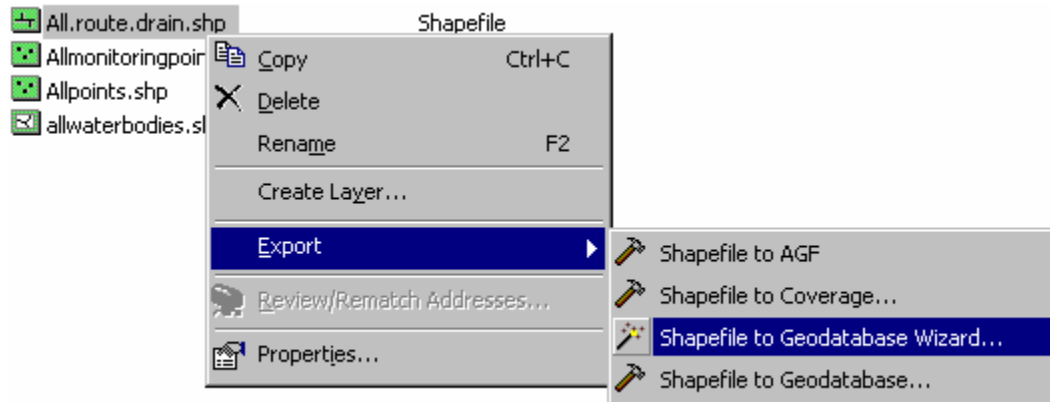
d. Import all of the other shapefiles into the newly created feature dataset. As you import them, assign them the following names:
    i.   River Reaches => HydroEdge (already added)
    ii. Waterbodies (that intersect river reaches) => Waterbody
    iii. Watersheds => Watershed
    iv. Monitoring Points => MonitoringPoint
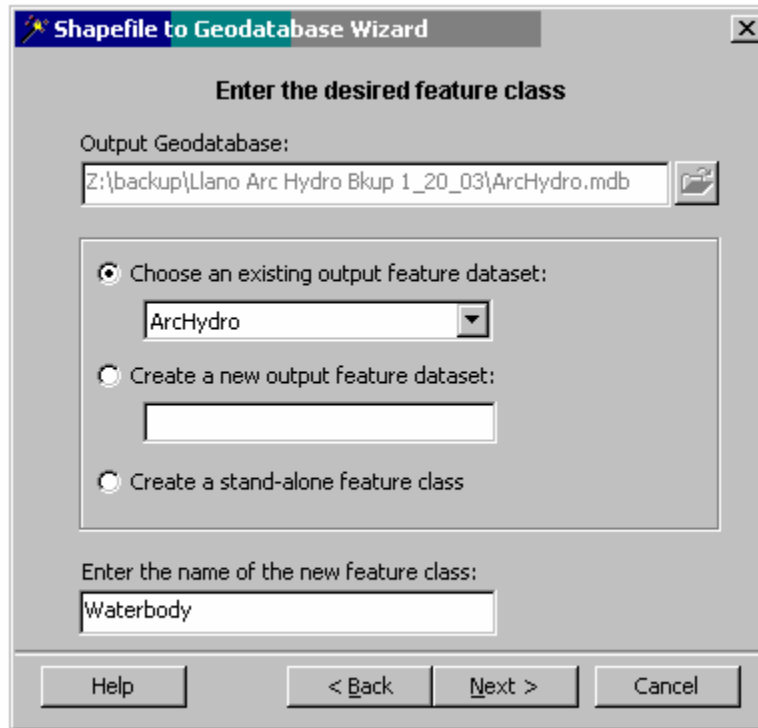
e. Inside the feature dataset create a new feature class named "HydroJunction". (When creating this feature class you will be presented with a number of dialogue boxes that let you adjust the parameters of the feature class. Use all of the default values, EXCEPT, under the Geometry Field you must change the Geometry Type from Polygon to Point).
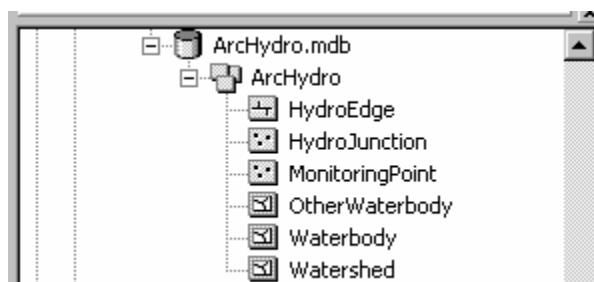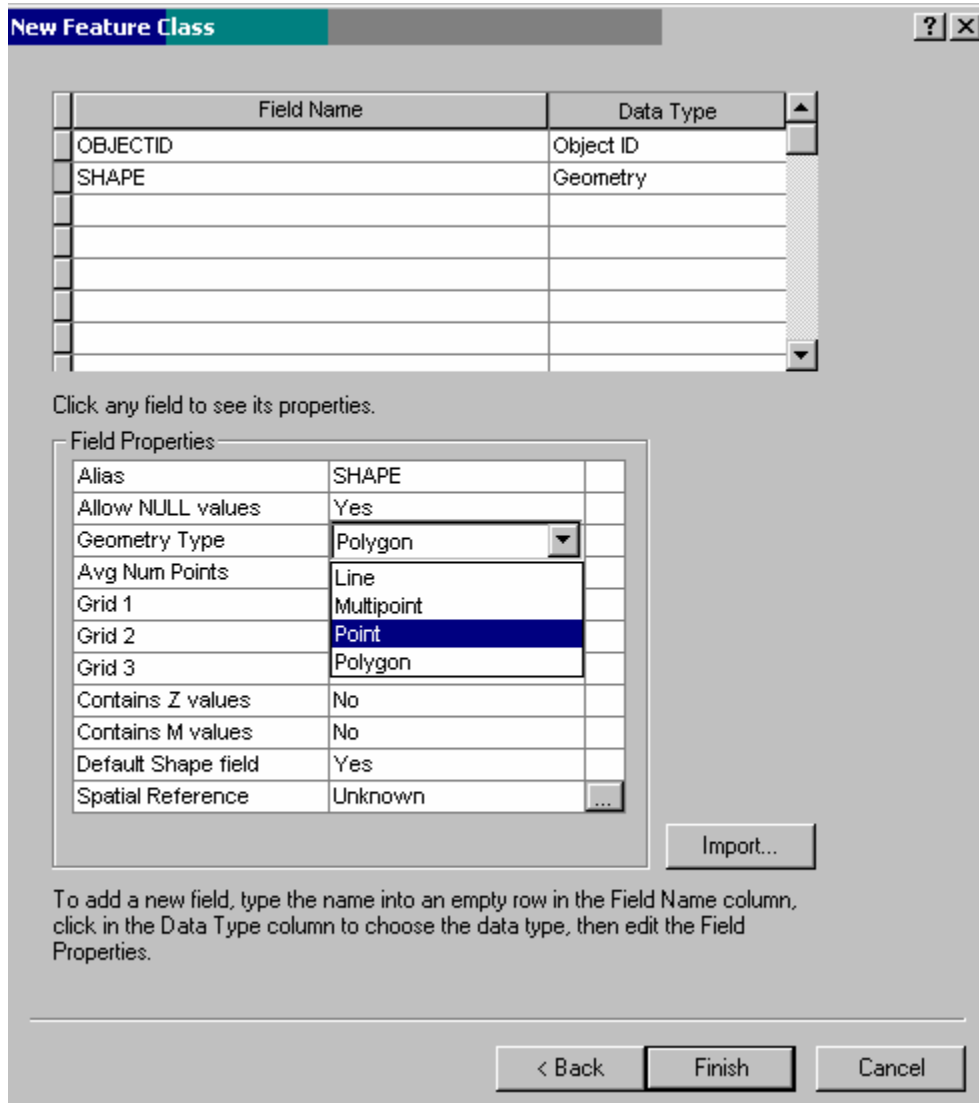
Resulting Arc Hydro Geodatabase

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4. Loading Monitoring Locations into the HydroJunction.

   The HydroJunction feature class is created to mark important locations along the Arc Hydro geometric network (created in Section 9). It will eventually include all watershed outlets, waterbody outlets, stream monitoring sites, etc. The following procedure details how to incorporate the stream monitoring points into the HydroJunction feature class. Note that the HydroJunction features will be snapped to the nearest HydroEdge feature, but the corresponding MonitoringPoint features will stay at their exact location. Also, note that the GageID field is only temporary; and is only used to "join" the MonitoringPoint and HydroJunction attribute tables.

   a. Load MonitoringPoint, HydroEdge, and HydroJunction into ArcMap.
   b. Open the MonitoringPoint attribute table and add the following fields: HydroID, GageID, JunctionID (data type = "long integer" for all fields).
   c. Open the HydroJunction attribute table and add the following fields: HydroID, GageID, FType (data type = "string" for Ftype and "long integer" for the others).
   d. Use ArcHydro attribute tools to assign HydroID values to MonitoringPoint.
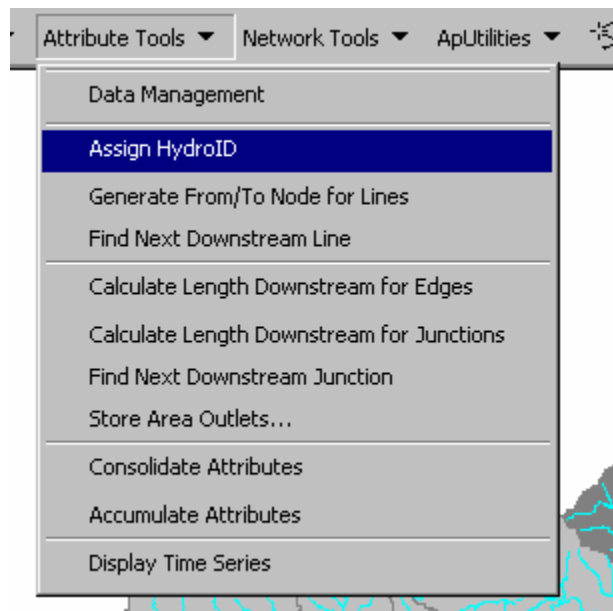
   e. Copy the MonitoringPoint HydroID field values to the MonitoringPoint GageID field (Use the "calculate values" command in the attribute table).
   f. Select all of the MonitoringPoint features that measure stream flow characteristics (i.e. do not select MonitoringPoint features that represent rainfall gages because these are not associated with the river network).
   g. Export this selection as a new feature class. Give it a name such as "StreamMPoint". (This is only a temporary feature class and will be deleted later.)

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h. Add the "Load Objects…" tool: {Tools>Customize>Commands>Data Converters>Load Objects…}

Load Objects...

The "Load Objects..." command is used to load one or more feature classes into a specified "target" feature class. The "target" is the feature class selected in the Editor toolbar. This command also allows for location adjustment of loaded features based on the Editor's snap settings. "Loading" objects transfers data from one feature class to another. ("Importing", as done in Part 3, creates a new feature class).

i. Start Editing and set Target to HydroJunction.
j. In the Editor, set Snapping to "edges" of HydroEdge and select "perpendicular to sketch". Set the Editors snap tolerance to 10,000 map units (maximum).
k. Use the Load Objects… tool (with snapping) to load the StreamMPoint layer into the HydroJunction Layer.   For the "matching source fields" choose GageID to match the target GageID, but chose "<None>" for the other fields.
l. Use ArcHydro attribute tools to assign HydroID values to HydroJunction.
m. Assign the value "MonitoringPoint" to the Ftype field of all HydroJunction features.
n. Copy the HydroID values from HydroJunction to the JunctionID field of MonitoringPoint using the following steps (or using Microsoft Access):
    i.   Join HydroJunction to MonitoringPoint based on GageID.
    ii. Turn on the Editor and open the MonitoringPoint attribute table.
    iii. Copy HydroJunction.HydroID to MonitoringPoint.JunctionID
o. The HydroJunction Layer should now include all of the StreamMPoint points. Make sure that all of these points have successfully snapped to the HydroEdge layer (you could use a "select by location…" command to determine this).
p. Wherever the HydroJunction points did not snap to HydroEdge, use the Editor to move and snap them to the HydroEdge layer manually.
q. Delete GageID fields from HydroJunction and MonitoringPoint.
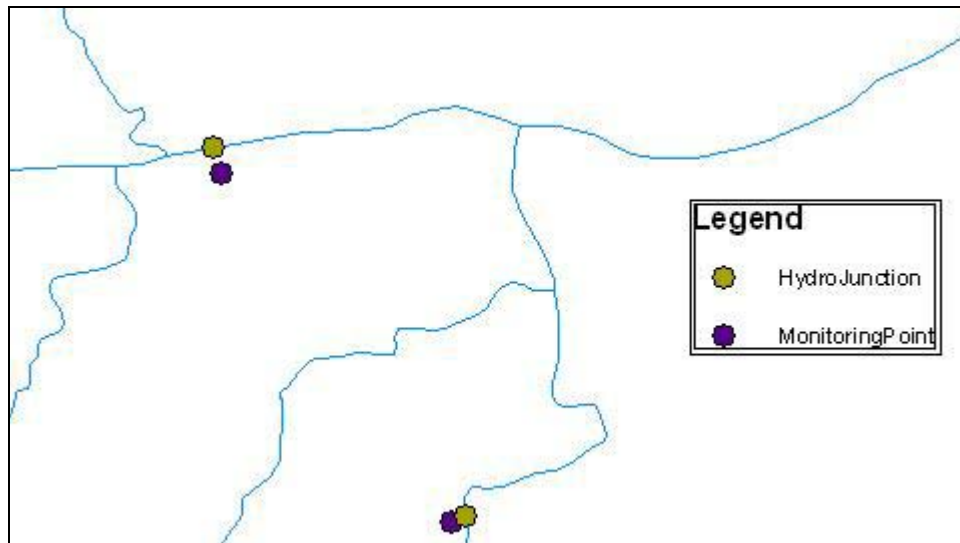
Resulting HydroJunctions and MonitoringPoints

5. Breaking HydroEdges at Locations of Interest.
    *The ultimate goal of Sections 5, 6, & 7 is to create HydroJunction features
    that represent watershed and waterbody outlet points. These features will
    originally be created as network junctions. When a network is created, it
    places generic network junctions at the intersections (breaks) of all network
    edges (HydroEdges in our case). Since network junctions are required at the
    outlet of each watershed and waterbody, make sure that the HydroEdge
    features are broken at these locations.*
    a. Load HydroEdge and Watershed into ArcMap.
    b. Use the Geoprocessing Wizard to intersect HydroEdge with Watershed.
        Give the output file a name such as "HydroEdgeI"
    c. If you are using NHD river reaches and waterbodies go to section 6.
        (NHD river reaches are already broken at waterbody intersections). If you
        are not using NHD data, repeat steps "a" and "b" for HydroEdgeI and
        Waterbody.

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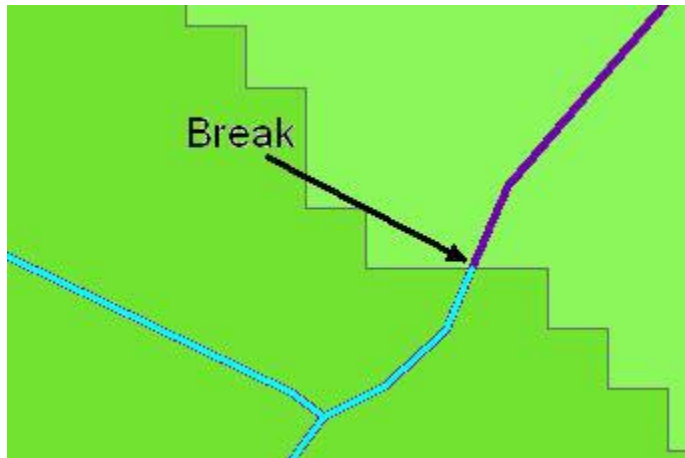
A HydroEdge broken at a watershed outlet

6. Creating WshOutlet (watershed outlets) and WbdOutlet (waterbody outlet) Features.
The networks created in this section are only intermediary networks and will be deleted later, in Section 8. The networks in this section are only being formed in order to help create the WshOutlet and WbdOutlet feature classes.
   a. In ArcCatalog, select to create a new geometric network in your project's feature dataset. Follow through the dialogue boxes:
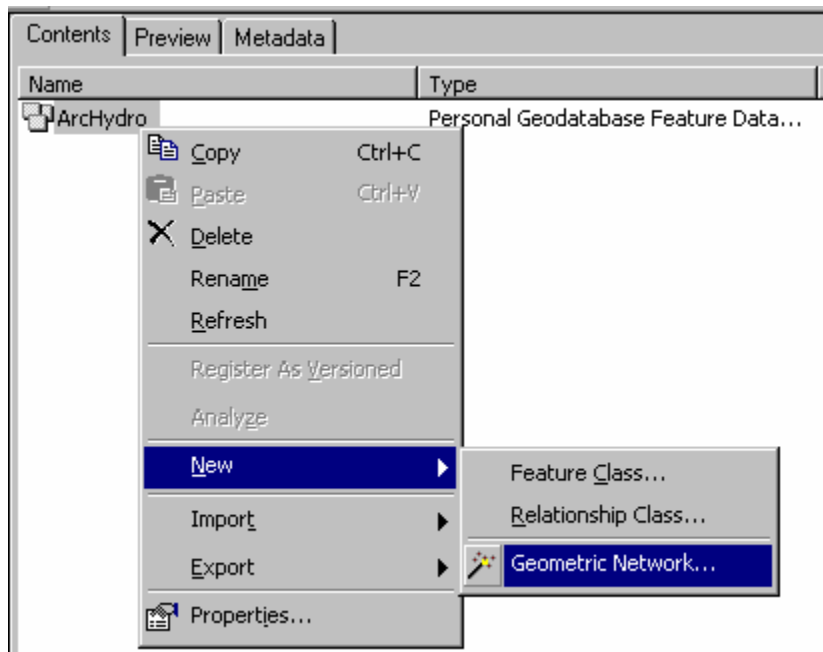
   i. Select "Build from existing Features
   ii. Select HydroEdgeI
   iii. Give the network a name such as "NetworkIYes"

           iv. Select Yes for complex edges
            v. Select No for snapping
           vi. Select No for assigning weights
          vii. Finish

b. Create a 2nd network:
             i. Select "Build from existing Features
           ii. Select HydroEdge
          iii. Give the network a name such as "NetworkINo"
           iv. Select Yes for complex edges
            v. Select No for snapping
           vi. Select No for assigning weights
          vii. Finish

c. Load NetworkIYes, NetworkINo, Watershed, and Waterbody into ArcMap.

d. Select by location NetworkIYes_Junctions that intersect NetworkINo_Junctions.

e. Open the attribute table for NetworkIYes_Junctions.

f. Switch the selection and close attribute table.

g. Export selected data to the feature dataset and name it "WshOutlet"

h. Zoom in at each watershed outlet location. Turn on the Editor and make the necessary adjustments. Make sure that (from most to least important, conditions i, ii, & iii must always be met):
             i. each watershed has only one outlet point.
           ii. watersheds do not share the same outlet point.
          iii. no outlet point is located at the intersection of streams.
           iv. each outlet point is located on the primary stream of the watershed it represents.
            v. each outlet is located inside or on the border of the watershed it represents.

Original Network
Output (Incorrect)

Modified Network
Output (Correct)
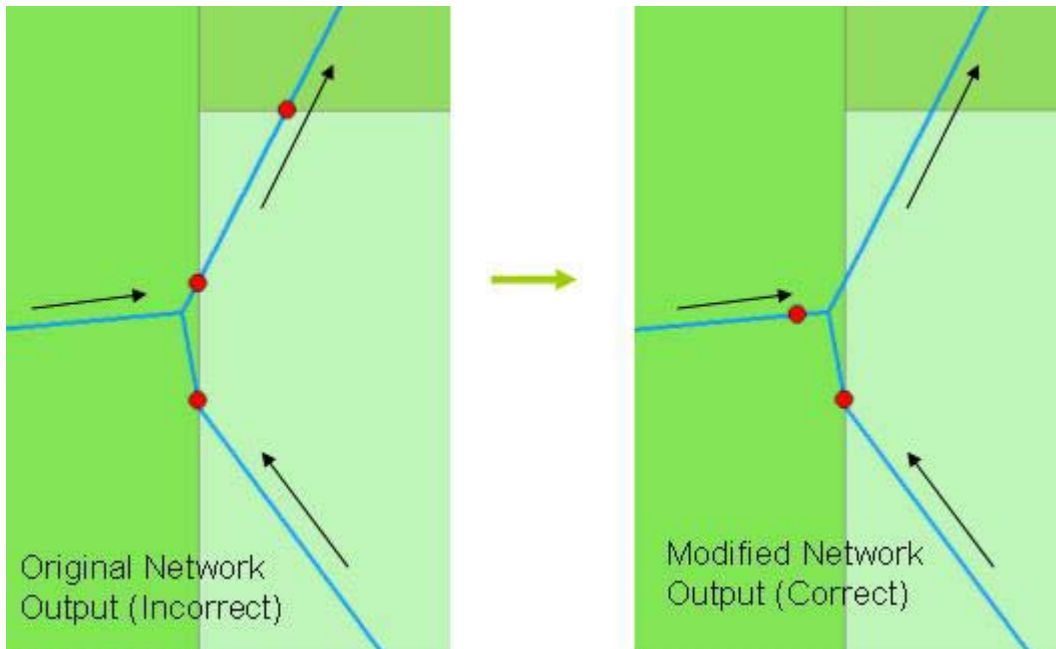
    i. Select NetworkIYes_Junctions that intersect Waterbody using an approximately 10 unit buffer.

    j. Export selected data to the feature dataset and name it "WbdOutlet"

    k. Zoom into each waterbody and delete excess outlet points (each waterbody should have only one outlet point). If necessary, use the network analyst to determine which point is the downstream outlet (perform a trace between the waterbody of interest and the basin outlet).

    l. Add the field "Ftype" to both WshOutlet and WbdOutlet. Assign the value "WshOutlet" to the Ftype field of all WshOutlet features. Assign the value "WbdOutlet" to the Ftype field of all WbdOutlet features.

7. Loading Outlets into HydroJunction.

    a. Load HydroJunction, HydroEdge, WshOutlet, and WbdOutlet into ArcMap

    b. Start Editing and set Target to HydroJunction.

    c. In the Editor, set snapping to "edges" in HydroEdge and select "perpendicular to sketch". Set the Editors snap tolerance to 10,000 map units (although this shouldn't be necessary since WshOutlet and WbdOutlet features should already be snapped to HydroEdge).

    d. Use the Load Objects… tool (snapping optional) to load the WshOutlet and WbdOutlet layers into the HydroJunction Layer. For the "matching source fields" choose Ftype to match the target Ftype, but chose "<None>" for the other fields.

Unlike the MonitoringPoint feature class, once the WshOutlet and WbdOutlet have been loaded into HydroJunction they may be discarded. However, it is not recommended that they be deleted because they are good back-up data.

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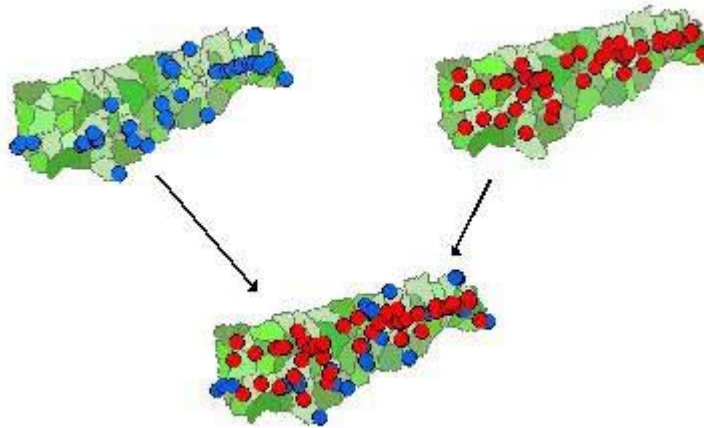
Symbolic view of outlets being loaded into the HydroJunction feature class.

8. Preparing Data for the Arc Hydro Network.
   This is the time to find any errors that may still exist within your feature classes. The networks created in Section 6 can be used to aid in this process. Then they must be deleted.
   a. Load NetworkIYes into ArcMap.
   b. Use Network Analyst to perform a trace to "find disconnected".

       i. Place a flag on any junction in the network

       ii. Run the trace
   c. Use the Editor to manually connect the disconnected river reaches. Close ArcMap.
   d. In ArcCatalog delete the existing networks.
   e. Load HydroJunction, Watershed, Waterbody, and HydroEdge into ArcMap.
   f. Use ArcHydro toolset to assign HydroID to all of the feature classes listed above. Make sure to NOT overwrite the existing HydroID values in HydroJunction.
9. Creating the Arc Hydro Network.
   It is now time to create the final Arc Hydro Geometric Network!
   a. In ArcCatalog, create a new geometric network:
       i. Select "Build from existing Features"
       ii. Select HydroEdge and HydroJunction
       iii. Preserve existing Enabled values (although, this shouldn't really matter)
       iv. Give the network the name "HydroNetwork"
       v. Select Yes for complex edges
       vi. Select Yes for snapping (use a tolerance of 1 map unit to be safe)
       vii. Select Yes for sinks/sources

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        viii. Select No for assigning weights
         ix. Finish
  b. Load HydroNetwork into ArcMap.
  c. Use the Network Analyst to check network integrity.
         i. Do a trace task to "find connected" (all network elements should be selected).
        ii. Do a trace task to "find disconnected" (no elements should be selected.)
       iii. If there were any problems with the network, fix the problem, delete the network and go back to step "9.a")

10. Setting Flow Directions.

Every HydroEdge feature can be either Enabled or Disabled. If a feature is Disabled, it will no longer be treated as part of the network. In most cases, all features should be kept enabled. Every HydroEdge also needs to be assigned a flow direction value. These values include: Uninitialized, With Digitized, Against Digitized, and Indeterminate. After completing this section, there should be no data left Uninitialized. Edges should only be set to Indeterminate if the designer cannot decide which way the flow is moving.

  a. Load HydroNetwork into ArcMap
  b. If there are any shorelines, select them and use the Editor and set these features' Enabled value to False.

  c. Display flow direction based on Network Connectivity:
         i. Turn on the Editor and select the basin's over-all outlet junction.
   ii. Using the attribute editor, set this junction's Ancillary Roll to Sink.
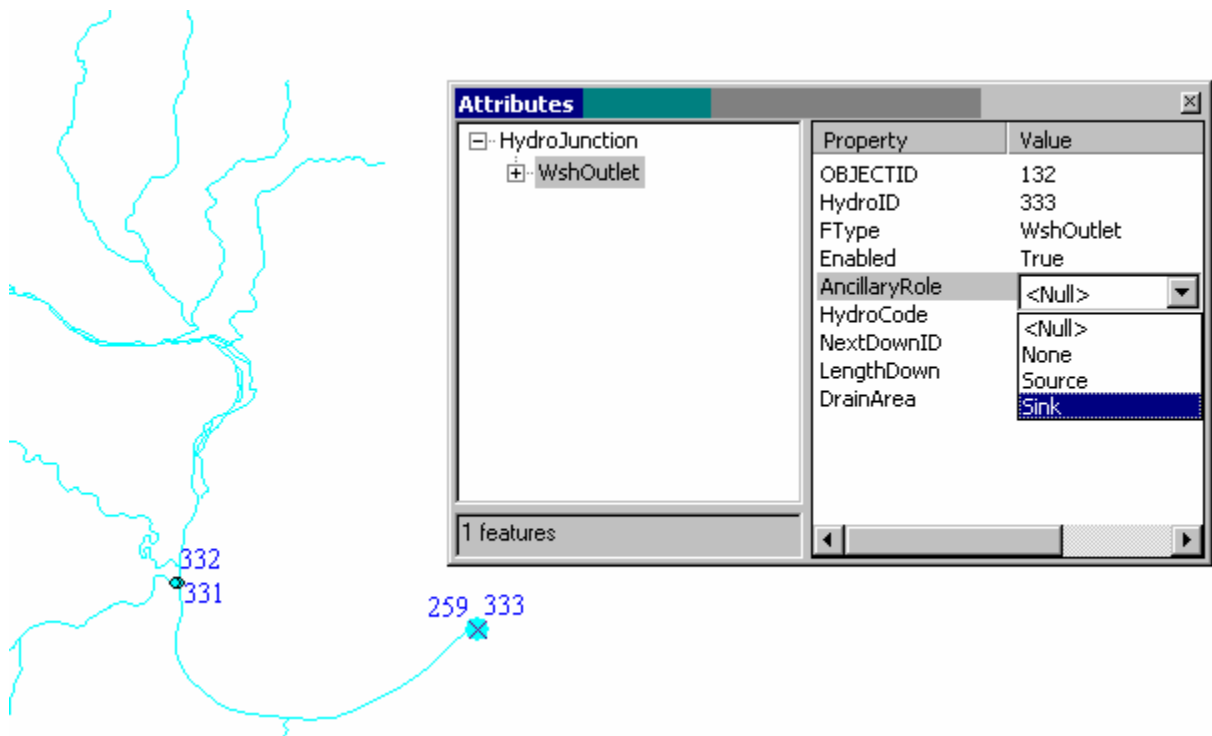
   iii. From the Network Analyst toolbar select the "set-flow-direction"

    button.   Turn off Editor.

   iv. From the Network Analyst toolbar select "Display Arrows"

 d. Go to the Arc Hydro Network tools and select "Store Flow Direction". (This stores the edges' flow directions as per the arrows shown on the screen. Directions are stored in the FlowDir field of HydroEdge.)

 e. Use Network Traces Upstream to determine where the flow direction has not been assigned (these are the locations of "loops" in your network, and are the areas where no flow direction has yet been assigned).

 f. IF a given loop is the result of an erroneous HydroEdge feature, turn on the Editor and set the feature's Enabled value to False.

 g. IF a given loop is the result of multiple river paths that truly exist, you will need to assign the flow direction manually using one of the following two methods:

   i. To assign flow direction values to ONE or MULTIPLE HydroEdge features:

    1. Select the features of interest.

    2. Change the HydroEdge symbology to "Arrow at End" (If the arrows are pointing the correct direction you want to assign the flow direction to "With Digitized". If the arrows are incorrect you want "Against Digitized."

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3. Select "Set Flow Direction…" from the Arc Hydro Network Tools. Select either With Digitized or Against Digitized
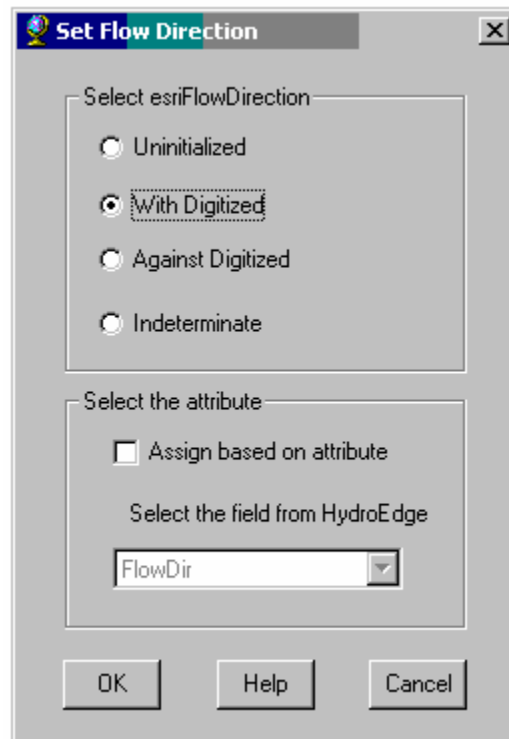

4. Select "Store Flow Direction" from the ArcHydro Network Tools.

ii. Use the Editor to manually assign flow direction to the FlowDir field of HydroEdge (FlowDir = 1 = With Digitized; FlowDir = 2 = Against Digitized)
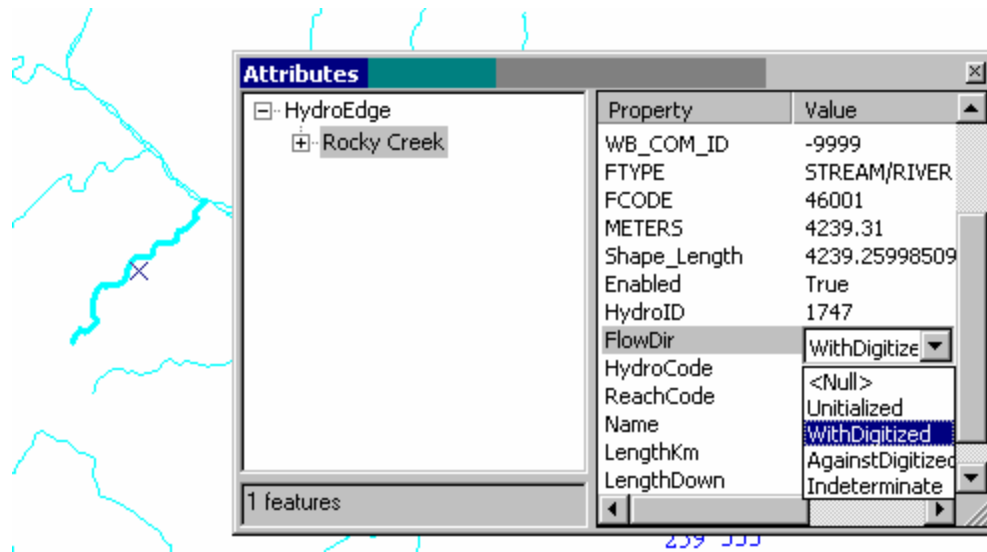
h. To determine that all flow directions have been logically assigned:
  i. Under {Network Analyst>Analysis>Options>Results} change the format from "drawing" to "selected".
  ii. Perform an upstream trace from the basin outlet.
  iii. Open the HydroEdge attribute table and switch the selection. (This will select any HydroEdge that does not have a logical flow direction assigned).
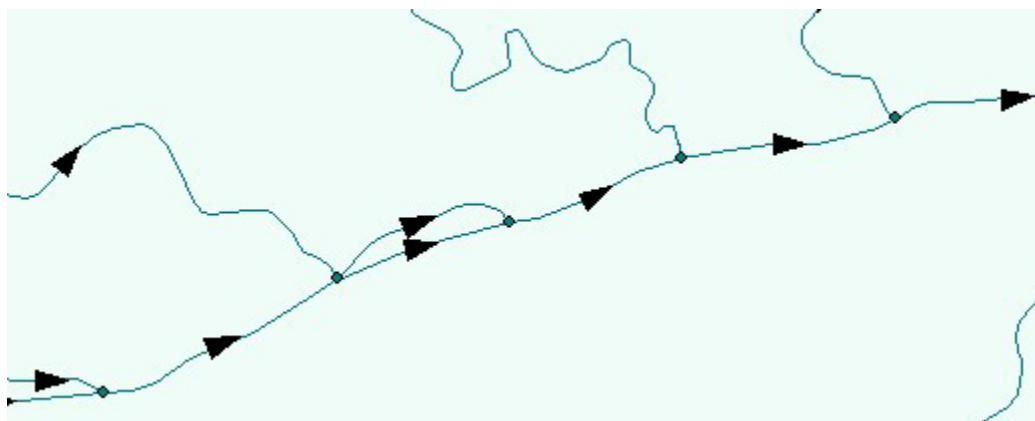
Properly Assigned Flow Directions

11. Implementing the Arc Hydro Schema.

Before the Schema can be applied, it is important to make sure all Arc Hydro fields have the correct data type assigned to them. Typically, the EdgeType and ReachCode fields must have their data types changed (to long integer and text, respectively). The following instructions are for changing EdgeType, but can be applied to any field.

a. Load HydroEdge into ArcMap.
b. Turn on the Editor and open the HydroEdge attribute table.
c. If the EdgeType field has unique values assigned to it, create a new field "EdgeType2" and copy the EdgeType values to it. (In most cases this isn't necessary)
d. Delete "EdgeType"
e. Add a new "EdgeType" field, and give it the correct data type (long integer).
f. If necessary, copy the values from EdgeType2 back to Edgetype and delete EdgeType2.

The Arc Hydro Schema applies a standardized database format to your Arc Hydro data. Most importantly, it creates relationships between feature classes (i.e. HydroJunctionHasMonitoringPoint). If your dataset is missing essential feature classes, the schema will create these as well (but, of course, they will be empty of data). In the future, the schema will need to be reapplied whenever data is revised or appended. It is also important to note that there are three types of schemata (framework, framework-w/timeseries, and full model). Here, we will just discuss the Arc Hydro Framework Schema, but the other schemas can be applied in a similar fashion.

g. Open ArcCatalog and add the "Schema Wizard" tool: {Tools>Customize>Commands>Case Tools>Schema Wizard}
h. Make sure your feature dataset is named ArcHydro. If necessary, rename it.
i. Select your geodatabase so that the ArcHydro feature dataset is visible, and click the Schema Wizard Button.
j. Continue through the dialogue boxes:
   i. Database Path = …\ArcHydroFrameworkSchema.mdb
   ii. Object Model = ArcHydroFramework Data Model :: ArcHydroFramework
   iii. For spatial reference, select "Use default values"
   iv. A tree-view of the dataset will be presented.
      1. Feature classes outlined in red have been automatically detected because they have the correct Arc Hydro standard name.
      2. Feature classes outlined in gray have not been detected. These feature classes can be assigned an existing feature class manually (Properties>Exists>Feature Class Already Exists…>Select).

3. If no data for a given feature class yet exists, leave the feature class outlined in gray.
4. Add fields to **each** feature class as necessary (this will create empty fields that can be filled in the future).
   a. Select the feature class.
   b. Select Properties>Exists
   c. Select each cell in the "In existing object" column that has the value "click to select". Change the value to "<Add field>"

v. Finish
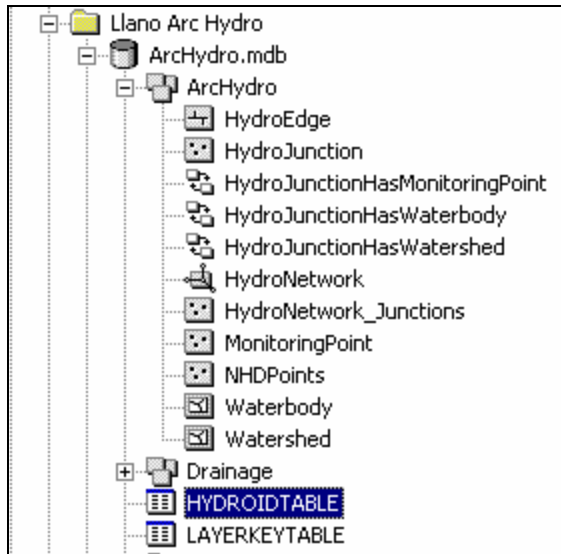
An example of a properly developed Arc Hydro Framework

12. Assigning Arc Hydro Attribute Values.

   The Arc Hydro Toolset and ArcMap Editor can be used to assign values to the empty attribute fields added at the end of section 11.

   a. Load HydroNetwork, Watershed, Waterbody, and MonitoringPoint into ArcMap.
   b. Turn on Editor. Add length and area values (in kilometers) to appropriate fields:
      i. In HydroEdge, compute: LengthKm = [Shape_Length/1000]
      ii. In Watershed, compute: AreaSqKm = [Shape_Area]/1000000]
      iii. In Waterbody, compute: AreaSqKm = [Shape_Area]/1000000]
   c. Select all of the HydroEdge features representing shore lines and set their EdgeType attribute value to 2.
   d. Select all of the HydroEdge features representing flow lines and set their Edge Type attribute value to 1. (This should be the majority, if not all of the HydroEdge features.)

e. Select "Compute Length Downstream for Edges" from the Arc Hydro toolset. Select to compute the downstream values for HydroEdge using LengthKm. (This fills the LengthDown field of HydroEdge.)
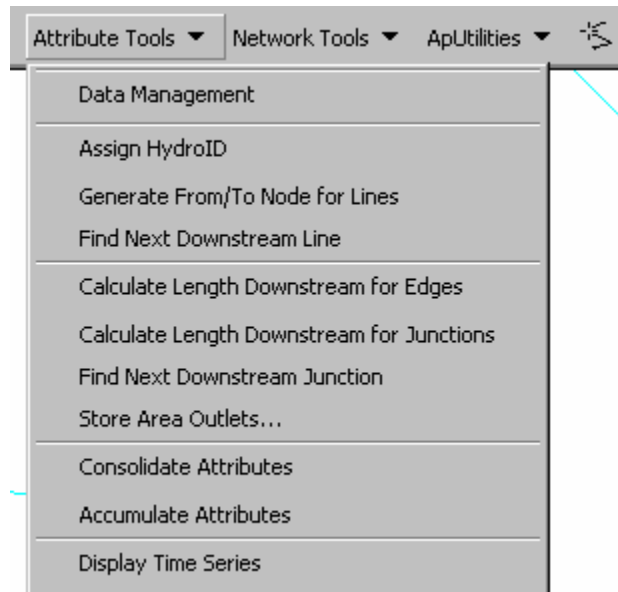
f. Select "Compute Length Downstream for Junctions" from the Arc Hydro toolset. Select to compute the downstream values for HydroJunction using LengthKm. (This fills the LengthDown field of HydroJunction.)
g. Select "Find Next Downstream Junction" from the Arc Hydro toolset. (This fills the NextDownID field of HydroJunction.)
The "Store Area Outlets…" command is used to fill the JunctionID fields for Waterbody and Watershed. JunctionID values are assigned based on the HydroID of the HydroJunction that represents the feature's outlet. To accomplish this, the "Store Area Outlets…" command provides several different methods for automatically determining which waterbody/watershed is associated with which HydroJunction. Experiment with these different methods to determine which is most appropriate for your model. In most cases, some JunctionID values will have to be assigned manually.
h. Select "Store Area Outlets…" from the Arc Hydro toolset. Select HydroJunction and Waterbody, to assign JunctionID's to Waterbody.
i. Label the HydroJunction features with their HydroID.
j. Label the Waterbody features with their JunctionID.
k. Use Editor to manually assign JunctionID's to Waterbody wherever the "Store Area Outlets…" command was not successful.
l. Repeat steps "h" and "k" for Watershed.
13. Finishing Up.
a. Delete extraneous fields and feature classes.

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b. Use ArcCatalog to develop Metadata for each feature class.
c. Step back and admire your work. You're done!

Appendix F: HMS IDM Database Diagram

ArcGIS HEC-HMS Interface Data Model (Draft)

Center for Research in Water Resources   The University of Texas at Austin

May 2004

Basin Geodatabase

ArcCatalog View

Reservoir Features

Diversion Features

Reach Features

Paired Data Tables

Paired Data Type

Paired Data

Transform Methods

S-Graph

Unit Hydrograph

Kinematic Wave

Clark unit hydrograph

ModClark (phidal)

SCS (Soil Conservation Service)

Snyder unit hydrograph

Watershed Transform Parameters

LossRate Methods

Deficit/Constant

Green & Ampt

Gridded SCS (Soil Conservation Service)

Gridded SMA (Soil Moisture Accounting)

Initial/Constant

SCS (Soil Conservation Service)

SMA (Soil Moisture Accounting)

Watershed LossRate Parameters

Routing Methods

Kinematic Wave

Lag

Modified Puls

Muskingum

Muskingum Cunge

Straddle Stagger

Muskingum-Cunge 8-Point

Reach Routing Parameters

Junction Features

Sink Features

Source Features

Basin Header

Hydrologic Modeling

Baseflow Methods

Bounded Recession

Linear Reservoir

Monthly Constant

Recession

Watershed Baseflow Parameters

Subbasin Features

Gridcells

Gridcell Header

Gridcell Tables

Timeseries Tables

Time Series Catalog

Time Series

Flow

Time

Created by: Dan Obenour, obenour@mail.utexas.edu

ArcGIS HEC-HMS Interface Data Model (Draft)

Center for Research in Water Resources   The University of Texas at Austin

May 2004

Project Geodatabase

Project Indices

Evapotranspiration
- Soil Moisture Accounting
- Evapotranspiration Zone Data

Project Header

HMS File Index

Basin Geodatabases

Project Tables Index

Scenario Management
- Controls
- Runs

ArcCatalog View

Grid Series Tables
- Grid Time Series Catalog
- Grid Time Series
- Grid Data Ranges

Gage Features

Time Series Tables
- Time Series Catalog
- Time Series

Grid Cell Features

Meteorological Parameters
- Distance Weighted Gage
- Distance Weighted Subbasin/Nodes
- Gridded Precipitation
- Frequency Storm
- Frequency Storm Subbasins
- User Hyetograph
- SCS Storm
- SCS Storm Subbasins
- Standard Project Storm
- Standard Project Storm Subbasins
- User Weighted Gage
- User Weighted Subbasins

Flow / Time

Appendix G: Instructions – "Populating a HMS IDM"

Populating the GIS-HMS Interface Data Model

Dan Obenour (8/30/03)

Introduction:

The GIS-HMS Interface Data Model (IDM) is a geodatabase format for storing the information found in a HEC-HMS project. The following instructions describe how to create the IDM and how to populate it using existing GIS and HMS files. The instructions assume that the user has a working knowledge of ArcMap and ArcCatalog.

Unlike the Arc Hydro data model, the IDM requires two or more geodatabases. One geodatabase represents data relevant to the entire HMS project; the other geodatabases represent data particular to individual basin files. The first part of these instructions describes how to develop a "Basin" geodatabase. The second part describes how to develop a "Project" geodatabase.

The repository and executable files referenced in these instructions are included in the report CD's, or they may be obtained from the following website:
http://civilu.ce.utexas.edu/stu/obenoudr/ahtohms.html

Part I – Basin Geodatabase

1. Apply the IDM Basin schema:
   a. Open ArcCatalog
   b. Create a new geodatabase. Any name is fine, but the following naming structure is suggested: *ProjectName_BasinName*Basin.mdb
   c. Select the geodatabase, and press the "Case Schema Creation" tool. This tool can be accessed through the following selections:
      {Tools>Customize> Commands>Case Tools>Schema Wizard}
         i. Select the repository file (Basin.mdb)
         ii. Proceed through dialogue boxes, no changes are necessary until the user arrives at the "Select the feature datasets to create" box.
         iii. Select the "HMSFeatures" feature dataset. Click on "Properties".
         iv. Edit the spatial reference frame so that it is appropriate for your project's location.
         v. Continue through the dialogue boxes. Finish.
   d. Exit ArcCatalog
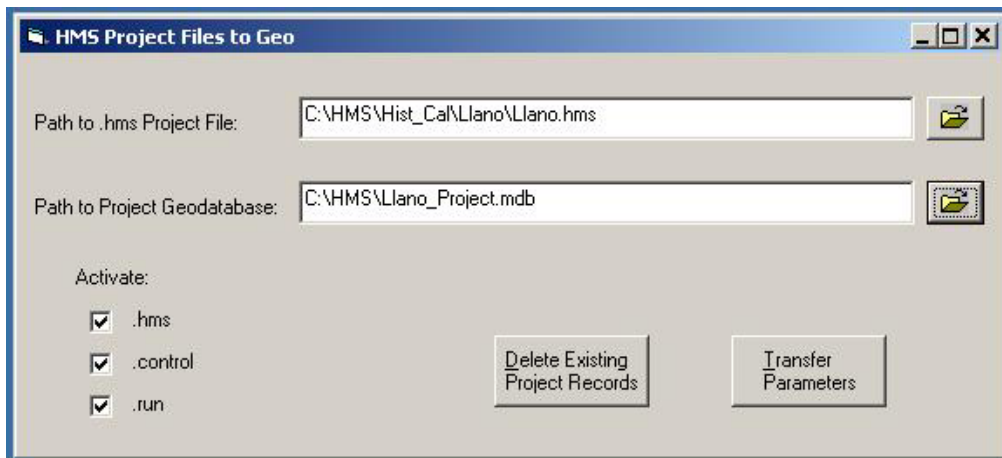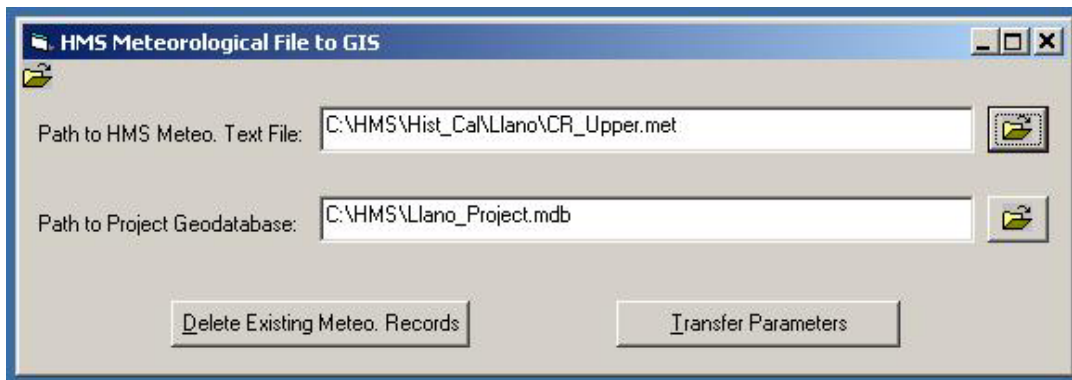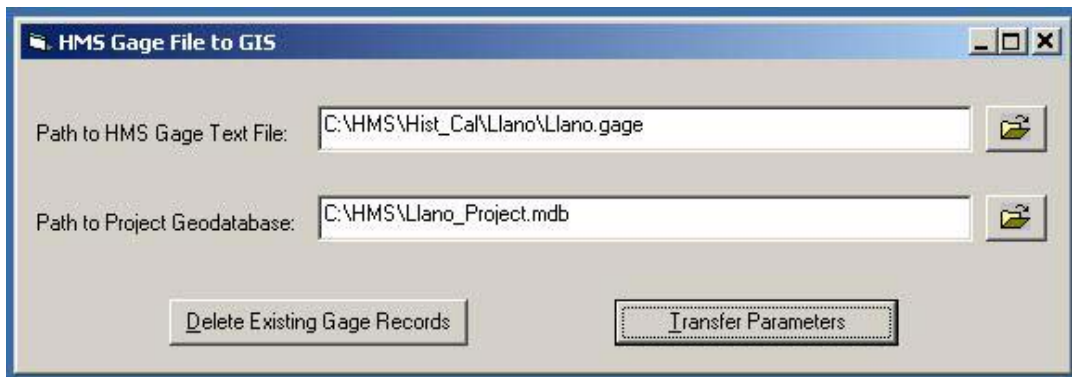
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2. Import HMS .basin file data
   a. Open BasinToGeo.exe program. (see image below)
      i. Top text box: Navigate to HMS .basin file
      ii. Bottom text box: Navigate to Basin Geodatabase
   b. Click "Transfer Parameters"
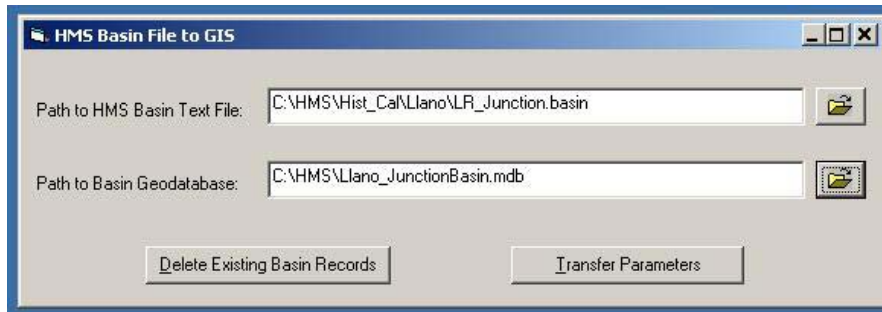
3. Import GIS shape data
   a. Verify that a geodatabase exists with all necessary shape data
   b. Verify that the geodatabase has a field with HMSCodes (so that the features in it can be matched with features in the IDM Basin Geodatabase)
   c. Open ShapesToGeo.exe program (see image below)
      i. Top, left text box: Navigate to geodatabase with shape data
      ii. Top, right text box: Navigate to Basin Geodatabase
      iii. Activate data transfer options, based on the Target Feature Classes you want to fill
      iv. Enter the names of the Source Feature Classes.
      v. Enter the names of the Source Fields that contain HMSCodes
   d. Click "Transfer Shape Data"
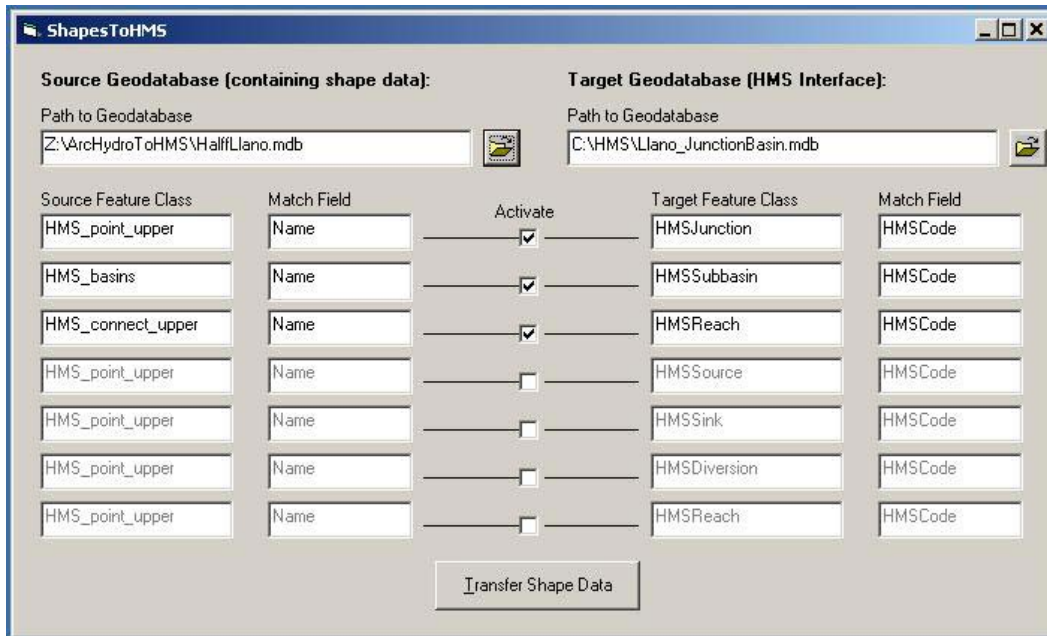
4. Import HMS paired data
   a. Open PDToGeo.exe program. (see image below)
      i. Top text box: Navigate to HMS .dss file
      ii. Bottom text box: Navigate to Basin Geodatabase
      iii. Click "Query Setup"
         1. Enter appropriate query information:
            a. For HMS Version 2.1, enter basin name in F-Part text box. All other boxes should be empty.
            b. For HMS Version 2.2, enter basin name in B-Part text box. Check "Check Basin name only". All other boxes should be empty
         2. Click "Finished"
   b. Click "Transfer Parameters"
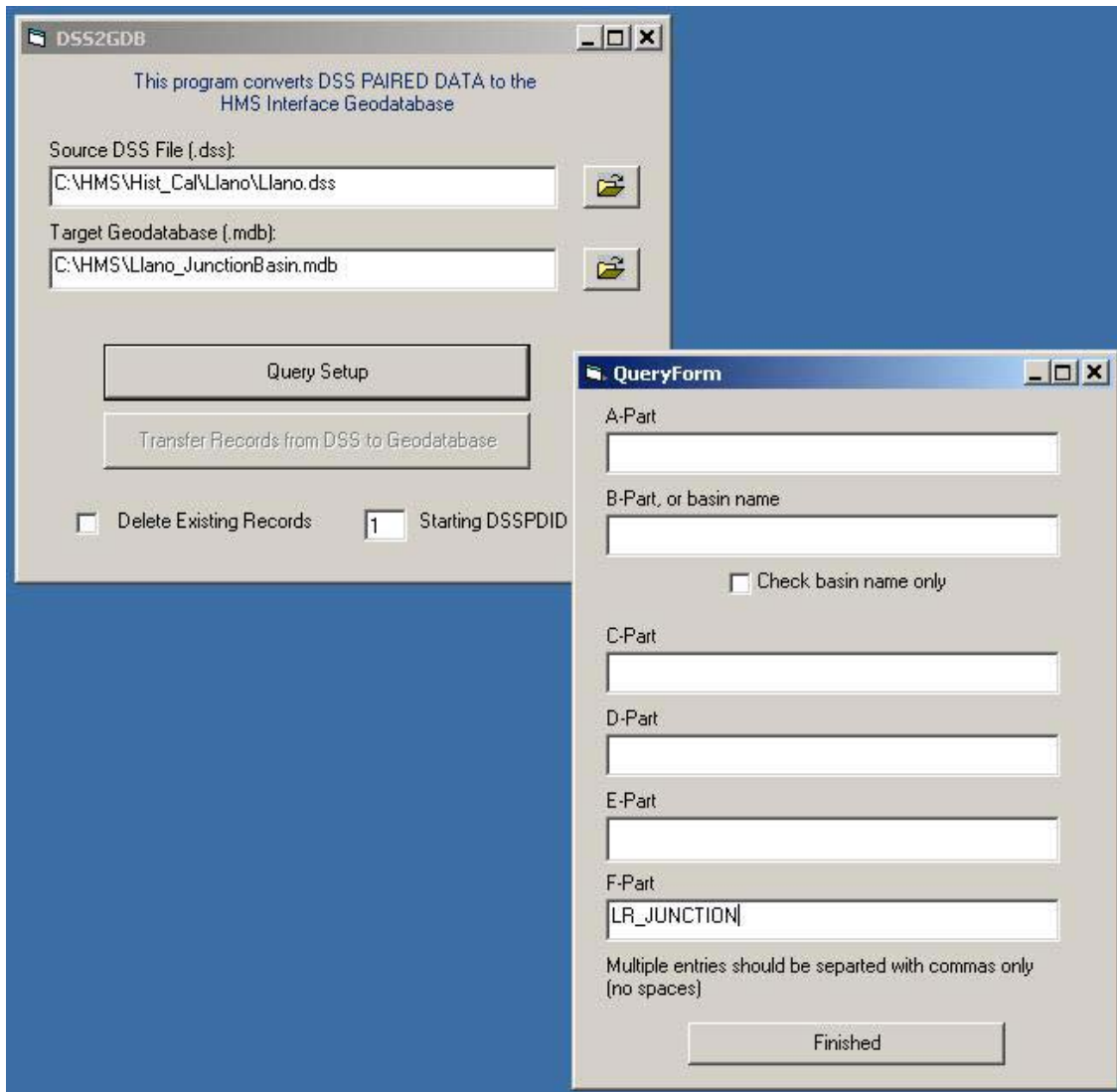
Part II – Project Geodatabase

5. Apply the IDM Project schema:
   a. Open ArcCatalog
   b. Create a new geodatabase. Any name is fine, but the following naming structure is suggested: *ProjectName*_Project.mdb
   c. Select the geodatabase, and press the "Case Schema Creation" tool. This tool can be accessed through the following selections:
   {Tools>Customize> Commands>Case Tools>Schema Wizard}
      vi. Select the repository file (Project.mdb)

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vii. Proceed through dialogue boxes, no changes are necessary until the user arrives at the "Select the feature datasets to create" box.

viii. Select the "HMSGage" feature class. Click on "Properties".

ix. Edit the spatial reference frame so that it is appropriate for your project's location.

x. Continue through the dialogue boxes. Finish.

d. Exit ArcCatalog

6. Import HMS .control, .run, and .hms file data

a. Open ControlsToGeo.exe program. (see image below)

i. Top text box: Navigate to HMS .hms file

ii. Bottom text box: Navigate to Project Geodatabase

b. Click "Transfer Parameters"

7. Import HMS .met file data
    a. Open MetToGeo.exe program. (see image below)
        i.   Top text box: Navigate to HMS .met file
        ii. Bottom text box: Navigate to Project Geodatabase
    b. Click "Transfer Parameters"
    c. Repeat for additional .met files.

8. Import HMS .gage file data
    a. Open GageToGeo.exe program. (see image below)
        i.   Top text box: Navigate to HMS .gage file
        ii. Bottom text box: Navigate to Project Geodatabase
    b. Click "Transfer Parameters"
    c. Optional: Follow the steps outlined in (Section 3) to import HMS gage shape data.

9. Import HMS timeseries data
   a. Open TSToGeo.exe program. (see image below)
      i. Top text box: Navigate to HMS .dss file
      ii. Bottom text box: Navigate to Basin Geodatabase
      iii. Click "Query Setup"
         1. Enter appropriate query information. Note: Because of the large size of DSS timeseries, attempting to import all data at once may not be possible. An alternative is to import data in a series of unique queries.*
         2. Click "Finished"
   b. Click "Transfer Parameters"
   c. Repeat until all timeseries data has been imported.*
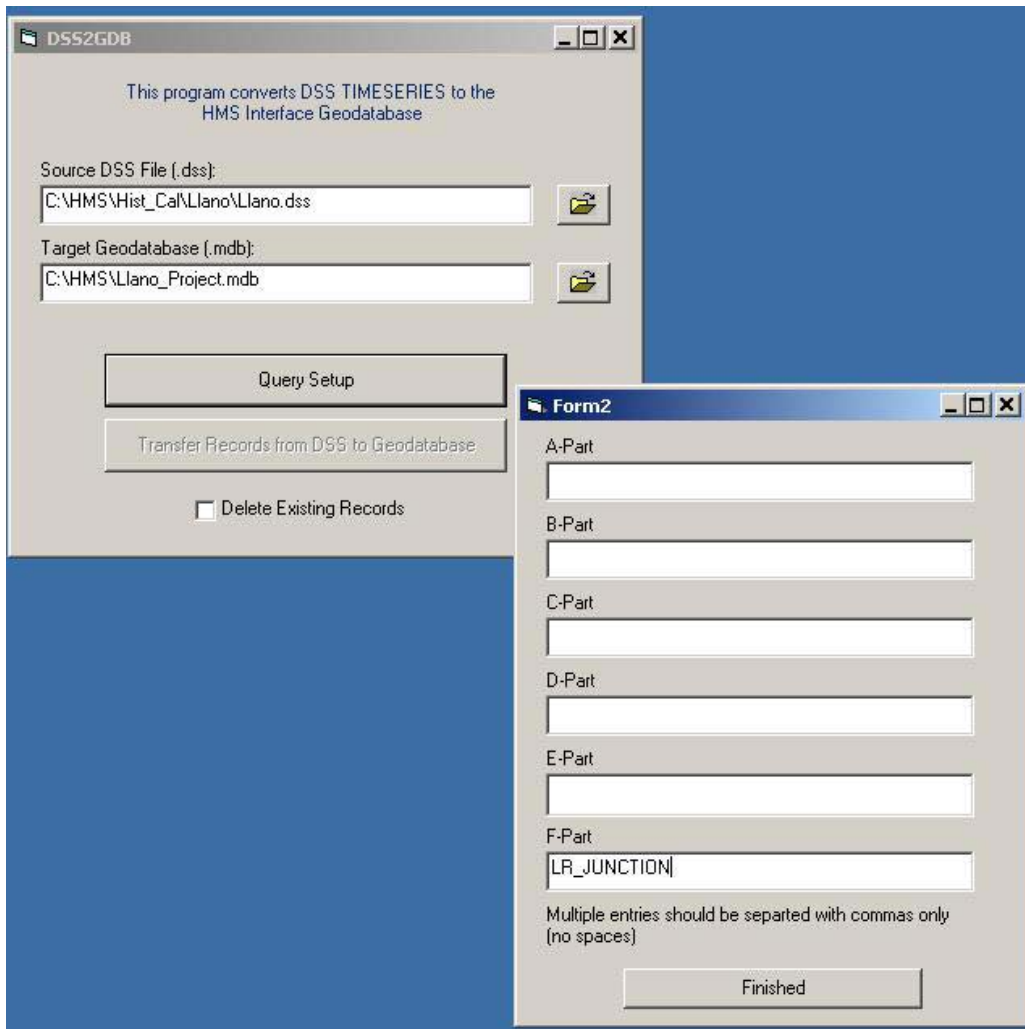
10. Finishing
   a. View all geodatabases in ArcMap to confirm that data is correct.
   b. Compact geodatabases in ArcCatalog to conserve disk space.

Appendix H: Instructions – "Preparation of Floodplain Mapping Data"

Preparation of Floodplain Mapping Data

Dan Obenour
1/21/04

I. Required Data:
    a. Halff land surface TINs
    b. Halff TIN boundary layer
    c. Halff RAS cross section layer
    d. Halff/LCRA floodplain layers
    e. Halff/LCRA HEC-RAS model
II. Preparation Procedure:
    a. In ArcCatalog prepare a geodatabase:
        i.   Select a region of interest (i.e. Bastrop)
        ii. Create a personal geodatabase with an appropriate name (i.e.Bastrop)
        iii. Create a feature dataset, and assign it a spatial reference equal to the extents of the LCR basin. Assign it an appropriate name (i.e. Bastrop)
        iv. Leave geodatabase empty
    b. In ArcMap prepare TIN boundaries and cross sections:
        i.   Load the TIN boundary layer and RASS cross section layer.
        ii. Select the TIN boundary polygon(s) relevant to the area of interest (i.e. Bastrop)
        iii. Export the selected polygon(s) to your personal geodatabase. Display this new layer. Remove the original TIN boundary layer from ArcMap
        iv. Select by location those cross sections that intersect the TIN boundary polygon(s).
        v.   Export the selected cross sections to your personal geodatabase. Display this new layer. Remove the original cross section layer from ArcMap.
    c. Prepare example water surface elevations:
        i.   Open the relevant HEC-RAS project
             1. View the output table for a representative storm event (i.e. 100yr flood)
             2. Under the File menu, select Copy Data and Headings to Clip Board
        ii. Open an empty Excel Spreadsheet
             1. Paste Data
             2. Delete all fields except "Station" and "W. S. Elev" (maximum)
             3. Make sure that there is only one heading row. (delete units row and any other extra heading rows)
             4. Delete any records that do not have a value for W.S. Elev
             5. Delete any text appended to station values in the station field (all values should be integer values)
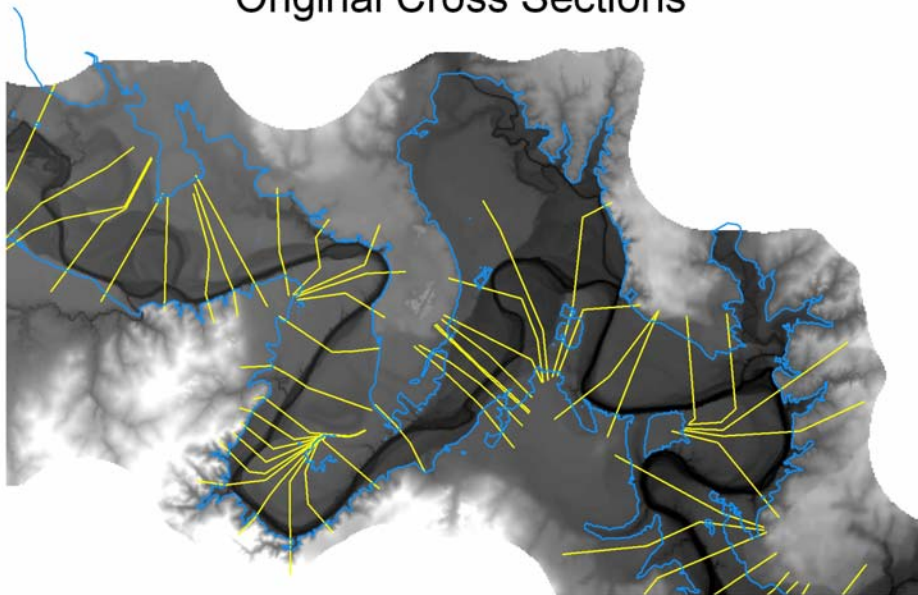
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6. Create a third field that equals [W.S. Elev]*100 (only a .dbf file can be imported into a geodatabase, and .dbf files do not support decimals)
7. Copy the values in this new field to clipboard
8. "Paste Special" these values into the "W.S. Elev" field. Delete the third field created in step 4.
9. Save spreadsheet as a dBase (.dbf) file.
   iii. Open ArcCatalog
1. Select the .dbf file and export this "Table to Geodatabase"
2. Export to the geodatabase created in part a.
   iv. Open ArcMap; load cross sections and water surface elevation table.
1. Join the water surface elevation table to the cross section table
2. Open the cross section attribute table
3. Select all cross sections that have a "WSElev" of Null (these should be only the most upstream and most downstream sections)
4. Close the attribute table. Turn on the Editor and delete these cross sections. Turn off the Editor.
5. Reopen the cross section attribute table, add a field with data type = <double> and name = "WSElev"
6. Add another field, with data type <text> and name = "Type"
7. Calculate WSElev = water surface values from joined table divided by 100 (i.e. WSElev = [Bastrop100.W_S__ELEV]/100)
8. Calculate Type = "main stem"
9. Remove Join
10. Use Symbology (color ramp) to display the variation in water surface between cross sections
d. In ArcMap, clip "tails" off TINs:
   i. Load the TIN boundary feature class into ArcMap
   ii. If this includes more than one TIN boundary, select and export the individual TIN boundaries into unique feature classes.
   iii. Load one TIN into ArcMap
   iv. Change the TIN symbology for faster viewing.
1. In Properties>Symbology, turn off "Elevation" and "Edge types"
2. Add… "Faces with the same symbol"
   v. Set the display of the TIN boundary feature class to 50% transparent
   vi. Verify that the relevant TIN boundary does not lie outside the TIN at any location. Where necessary, edit the TIN boundary. Buffering the TIN boundary (i.e. -20 feet) is often an effective solution.
   vii. Turn off the TIN display, but don't remove.
   viii. Clip the TIN. From the 3D Analyst, select Create/Modify TIN > Add Features To TIN

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             1. Select your input tin, and select the appropriate tin boundary layer. For the tin boundary layer, select height source = none, triangulate as = soft clip, Tag value field = none.
             2. Select "Save changes into the input TIN specified above". Okay.
             3. Repeat steps for each relevant TIN

   e. Convert TINs to raster (DEM).
      i. Open ArcMap
     ii. From 3D Analyst, select Convert > TIN to Raster
             1. Select an appropriate input TIN
             2. Attribute = Elevation, Z-factor = 1, Cell Size = 20',
             3. Assign an appropriate name: (i.e. "dem9")
             4. repeat steps for each relevant TIN
    iii. If there are multiple relevant TINs/rasters, then the rasters should probably be merged together. Open ArcInfo Workstation, type the following:
             1. grid <enter>
             2. *path\newgridname* = merge(*path\grid1*, *path\grid2*, …) (i.e…c:\temp\bastropdem = merge(c:\temp\dem9, c:\temp\dem10))

   f. Modify Cross Sections in ArcMap:
      i. Load the 500yr, 100yr, and 2yr floodplain layers into ArcMap (for reference)
     ii. Load the relevant DEM into ArcMap (for reference)
    iii. Turn on the Editor, and select the Modify Feature Task
    iv. Select and modify cross sections so that they extend beyond the extent of the 500 yr floodplain (see figure)
     v. Where large coves exist, add new cross sections. Assign these cross sections the station number, steam ID, reach ID, and elevation of an appropriate nearby cross section. In the Type field, assign a value of "cove" (see figure)
    vi. Where the river is sinuous, add tails to the end of cross sections that approach each other (see figure)
    vii. Where original cross sections converge to nearly a single line, clip these lines (see figure)

Modified Cross Sections

Tails Added (many locations)

Added Cove Section

Added Cove Section

Clipped Converging Sections

Original Cross Sections

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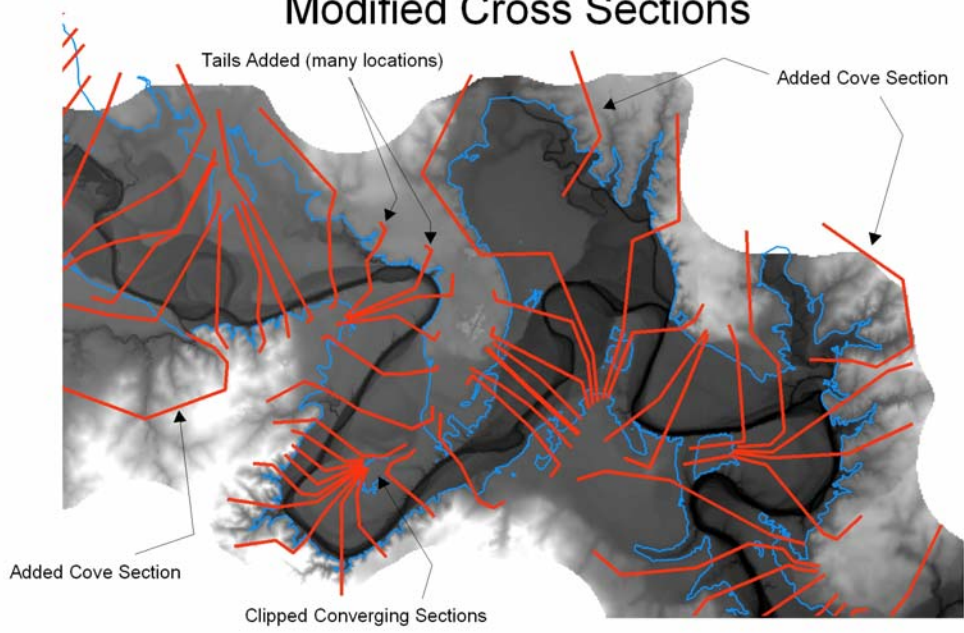
III. Procedure for testing the modified cross sections.
   a. Load modified cross sections, tin boundary, DEM, and Halff 100yr and 500yr floodplains into ArcMap
   b. From 3D Analyst, select "Create TIN From Features"
       i.   Select tin boundary, no values, soft clip
       ii. Select cross sections, WSElev, soft line
   c. Examine the resulting TIN relative to the 100yr and 500yr floodplains. Make sure that the floodplains are assigned appropriate water surface elations. Pay particular attention to coves and sinuous areas. If necessary, modify cross sections and recreate TIN.
   d. From 3D Analyst, select Convert > TIN to Raster
       i.   Select the water surface TIN
       ii. Attribute = Elevation, Z-factor = 1, Cell Size = 20',
   e. From Spatial Analyst, select Raster Calculator
       i.   Use the expression [*waterSurfaceRaster*] > [*DEMraster*] (the resulting Boolean raster will have a cell value of 1 where inundation occurs, and a cell value of 0 where the land stays "dry")
   f. From Spatial Analyst, select "Convert Raster to Features"
       i.   Input Raster = previous Calculation
       ii. Field = Value, Geometry = Polygon
   g. Delete "dry" features
       i.   Open feature class attribute table
       ii. Select by attribute GridCode = 0
       iii. Exit attribute table
       iv. Turn on Editor
       v.   Delete selected features
       vi. Finish Editing

Compare the resulting 100yr floodplain polygon to the Halff 100yr floodplain.

Appendix I: Model Builder Layouts

Model: GenerateFloodPlainOnly

Toolset: Generate New Results
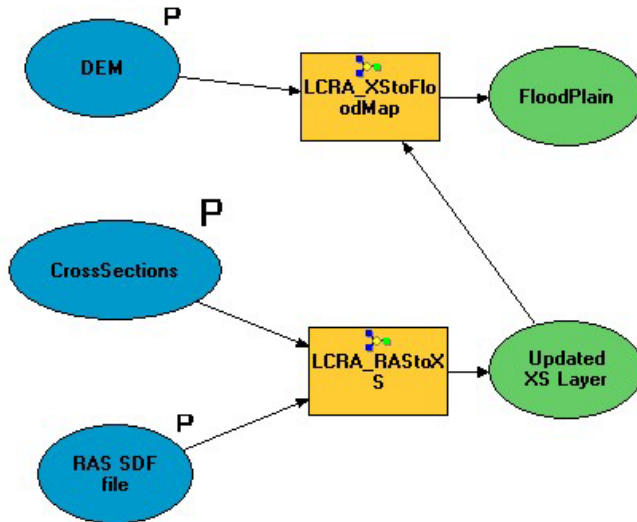
Model: GenerateDamageReportOnly

Toolset: Generate New Results

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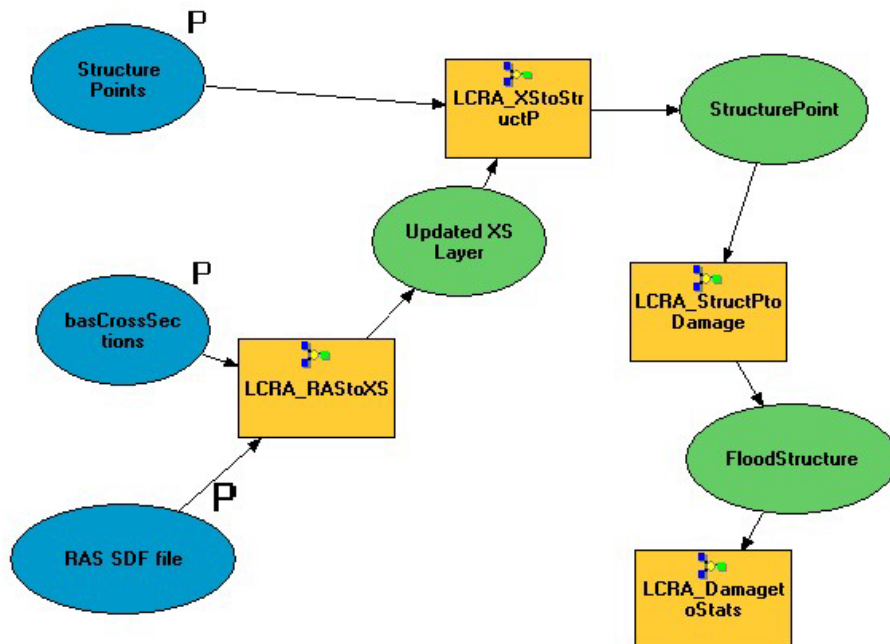
Model: GenerateAll

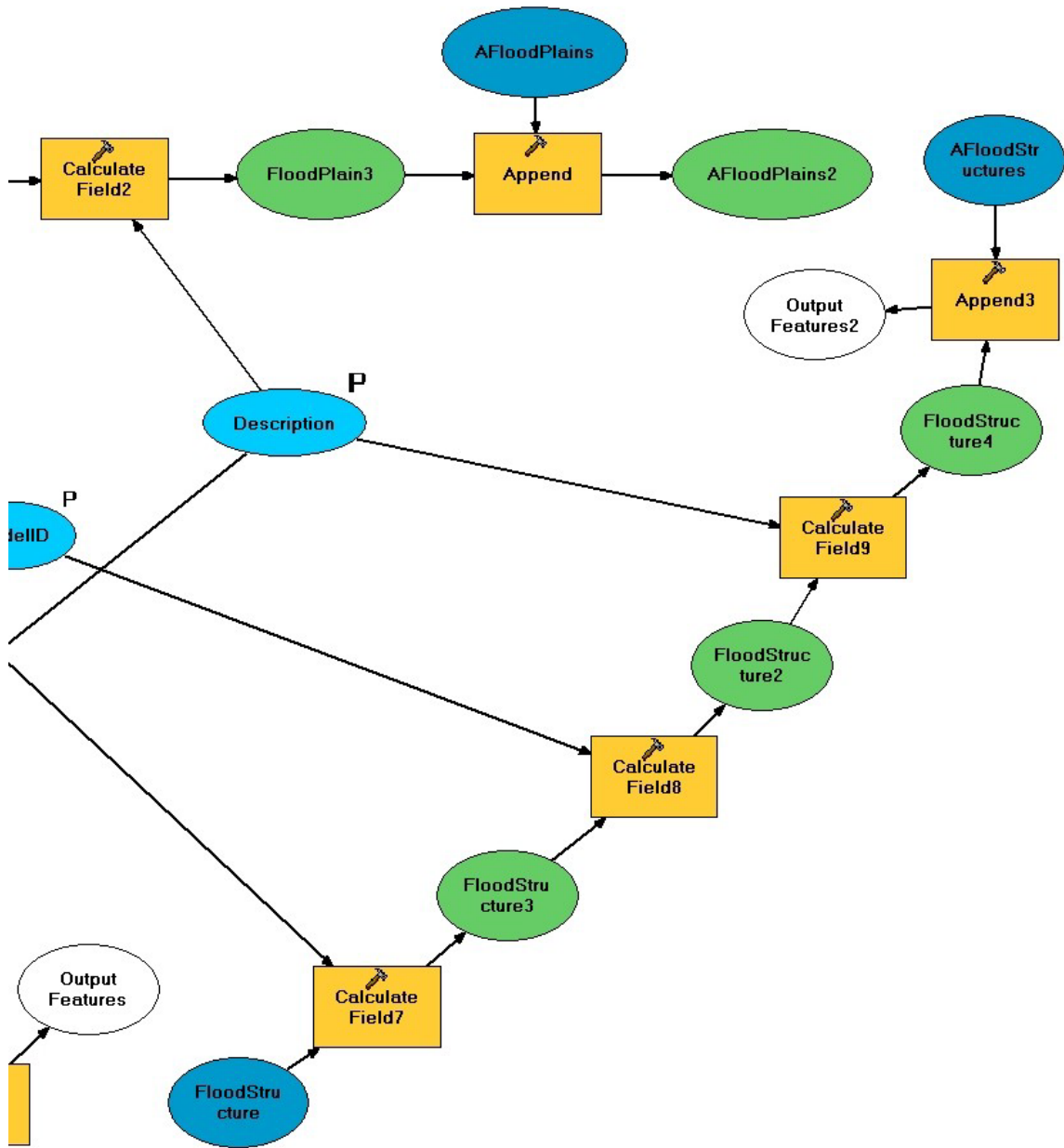Toolset: Generate New Results
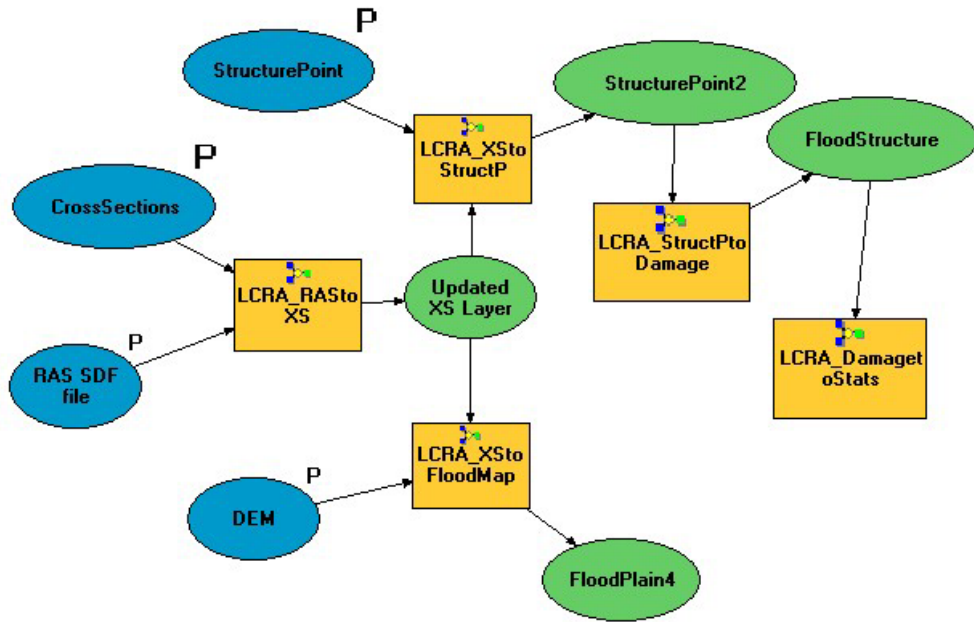
Model: ArchiveNew

Toolset: Manage New Results
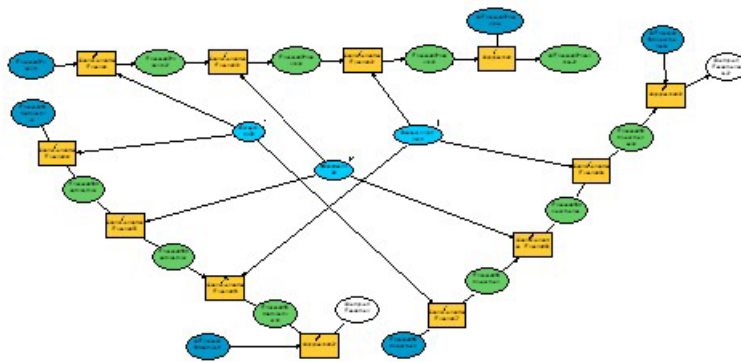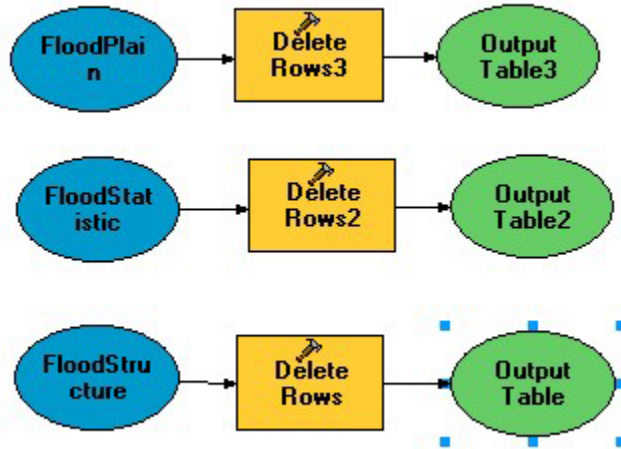

(See following pages for higher resolution graphics)

Model: ArchiveNew (sheet 1 of 2)
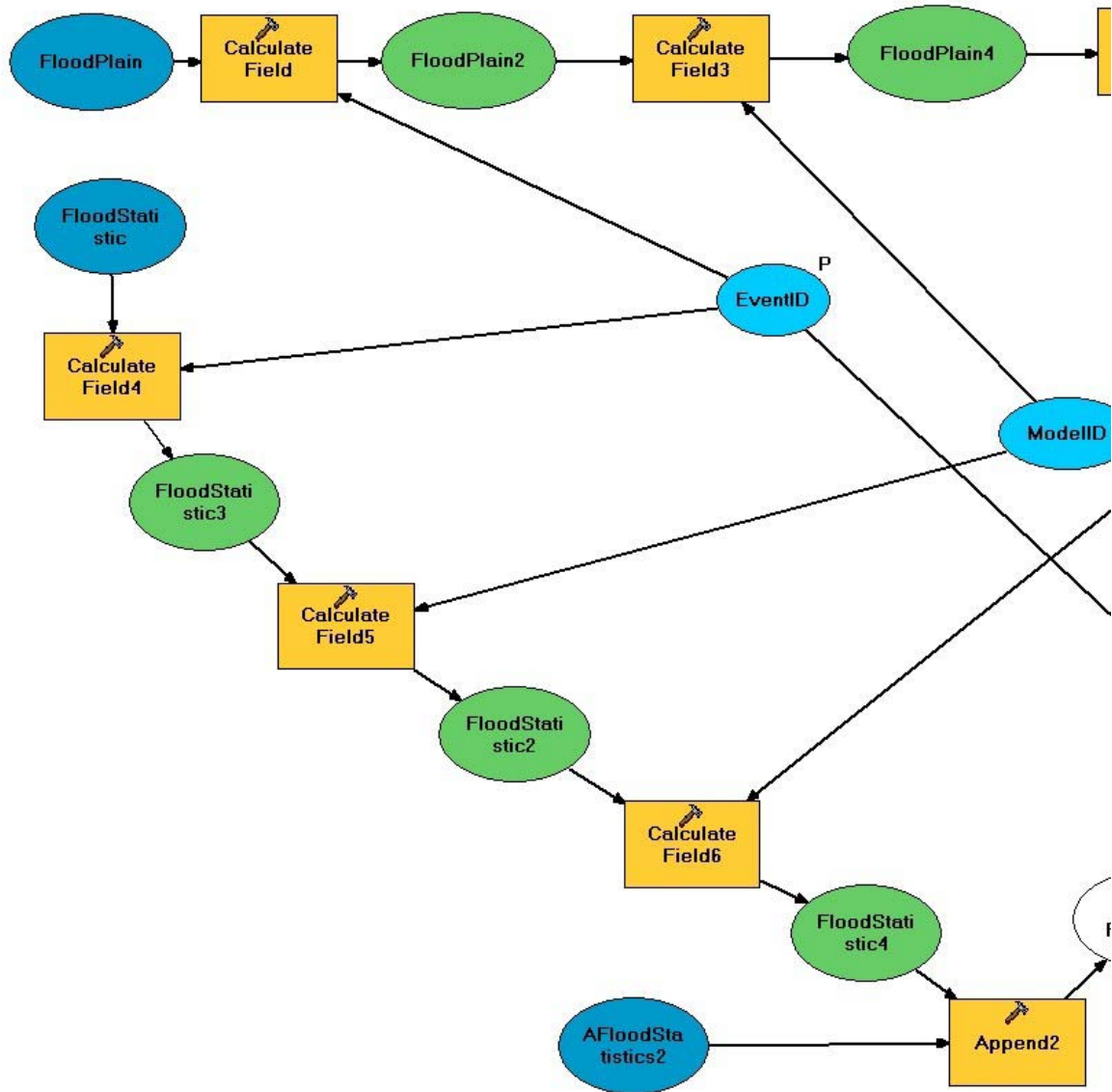
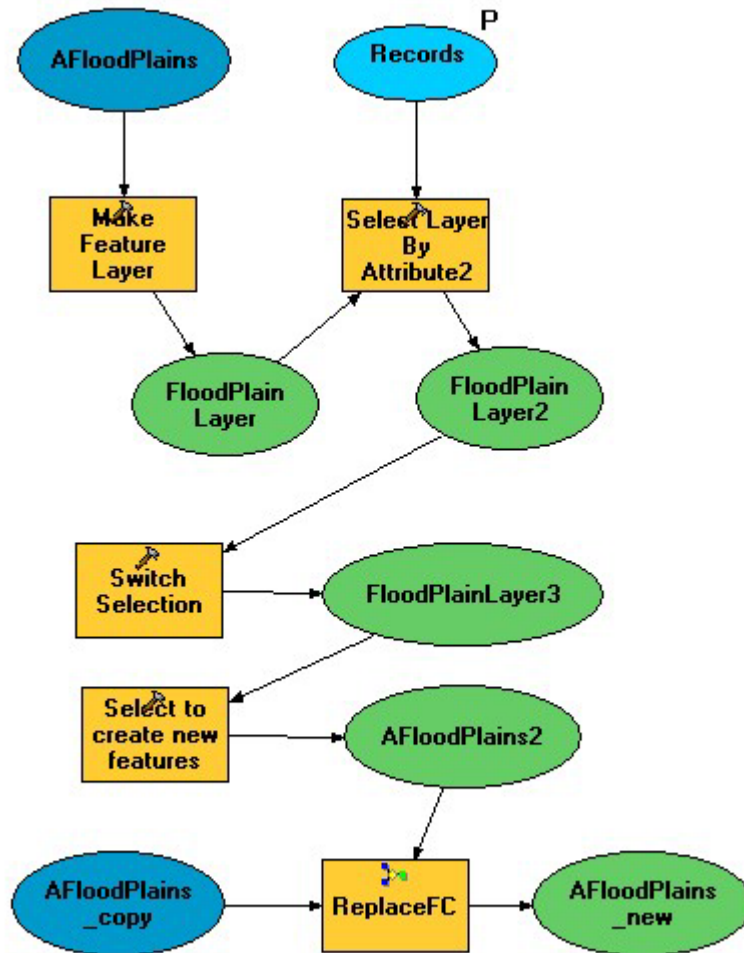Model: DeleteNewAll
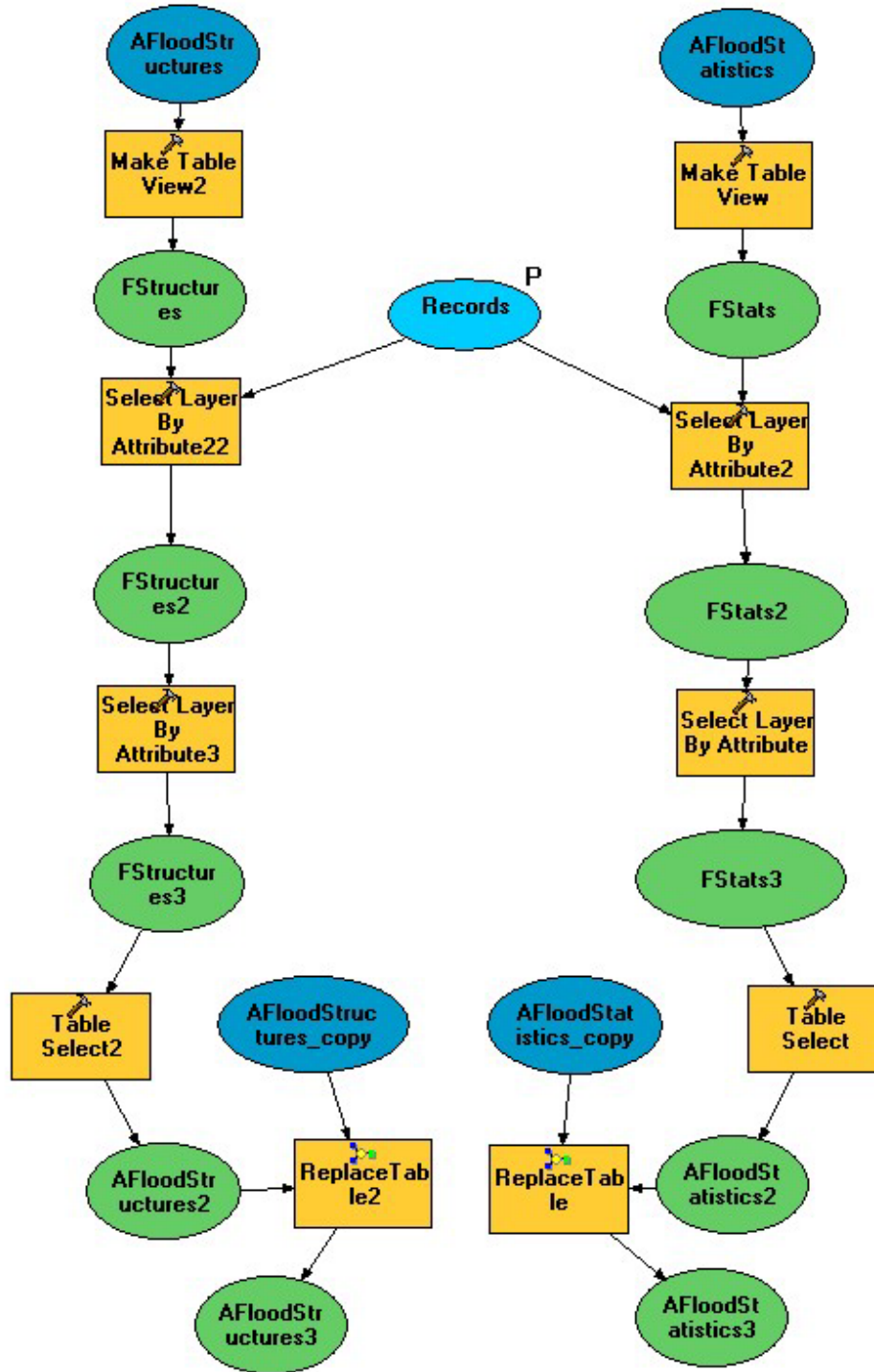
Toolset: Manage New Results
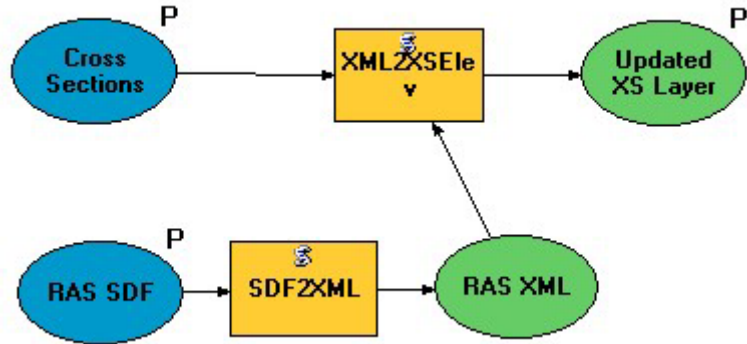
Model: DeleteArchivedFloodPlain

Toolset: Manage Archived Results

Model: DeleteArchivedDamageReport

Toolset: Manage Archived Results

Model: LCRA_RAStoXS

Toolset: Components

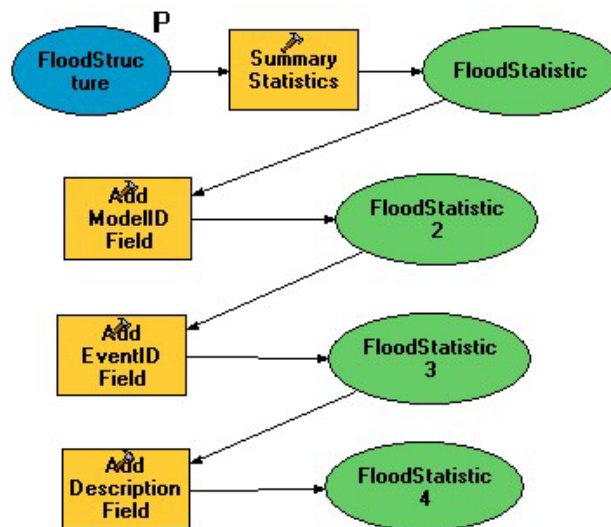Model: LCRA_XStoStructP

Toolset: Components
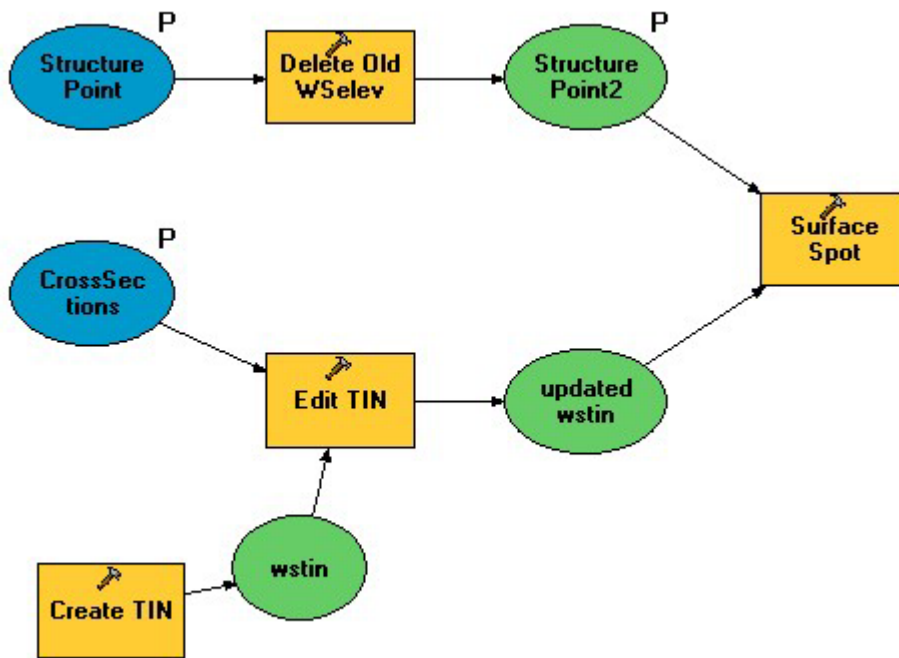
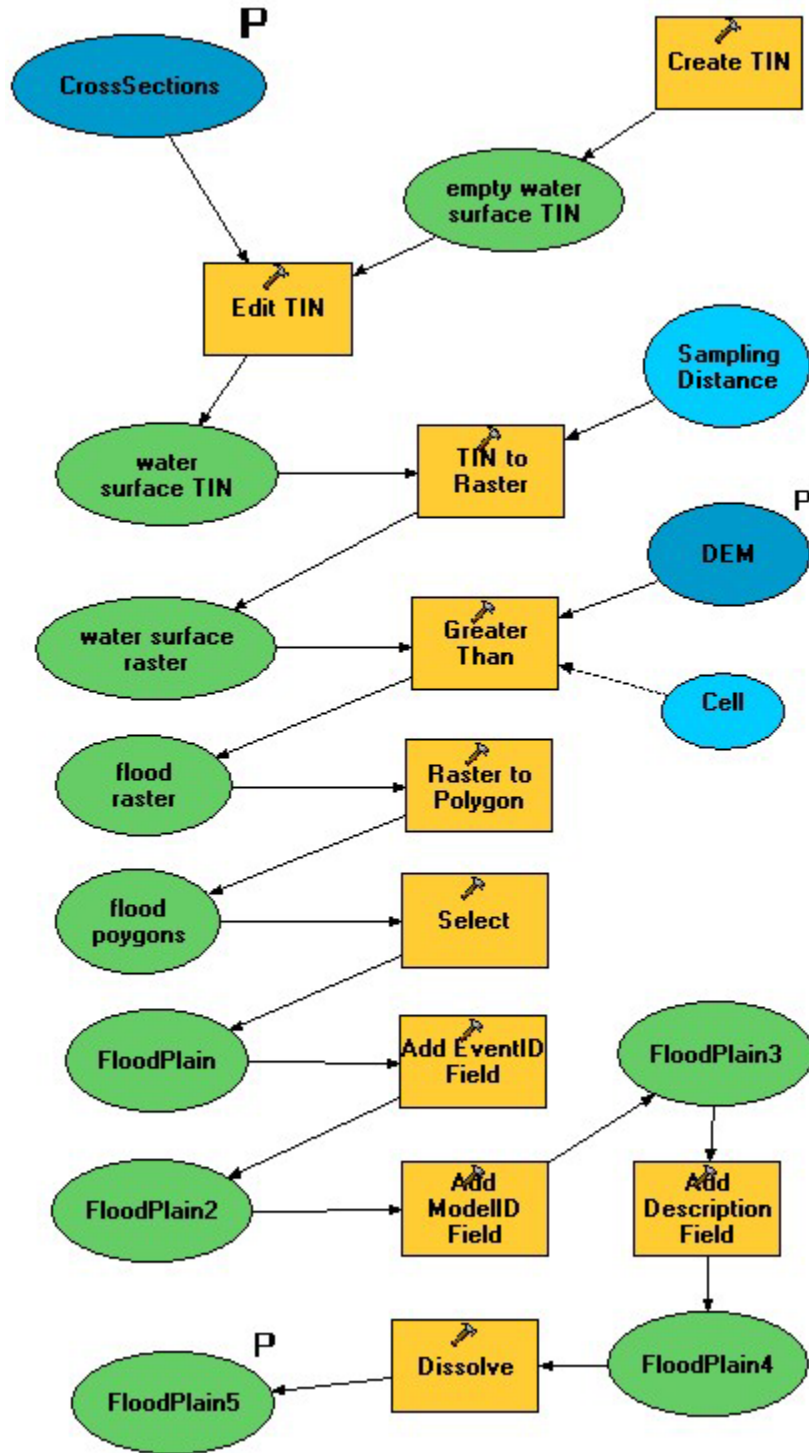Model: LCRA_StructPtoDamage

Toolset: Components
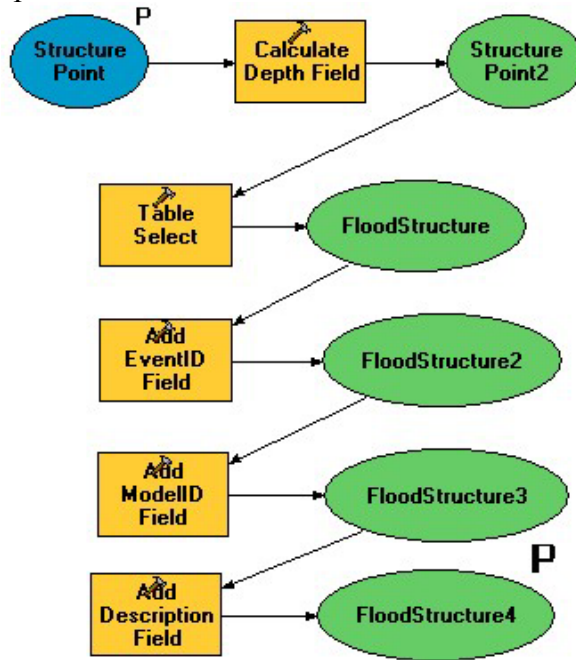
Model: LCRA_RAStoXS

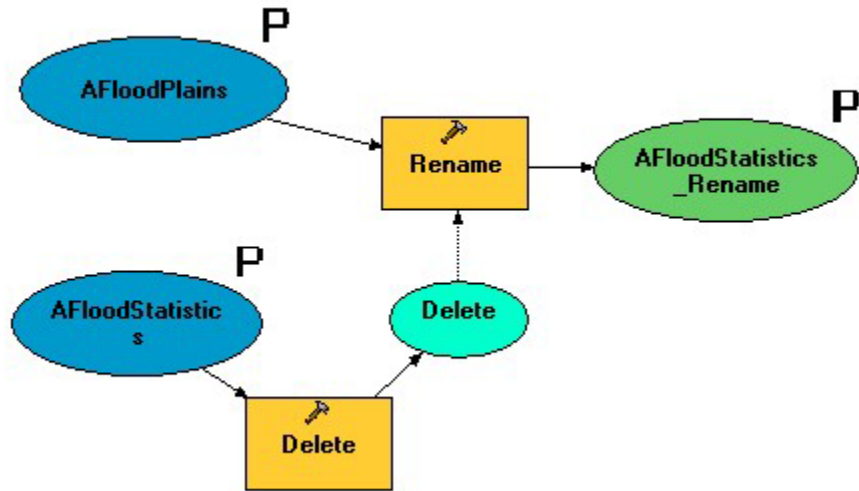Toolset: Components

Model: LCRA_XStoFloodMap

Toolset: Components
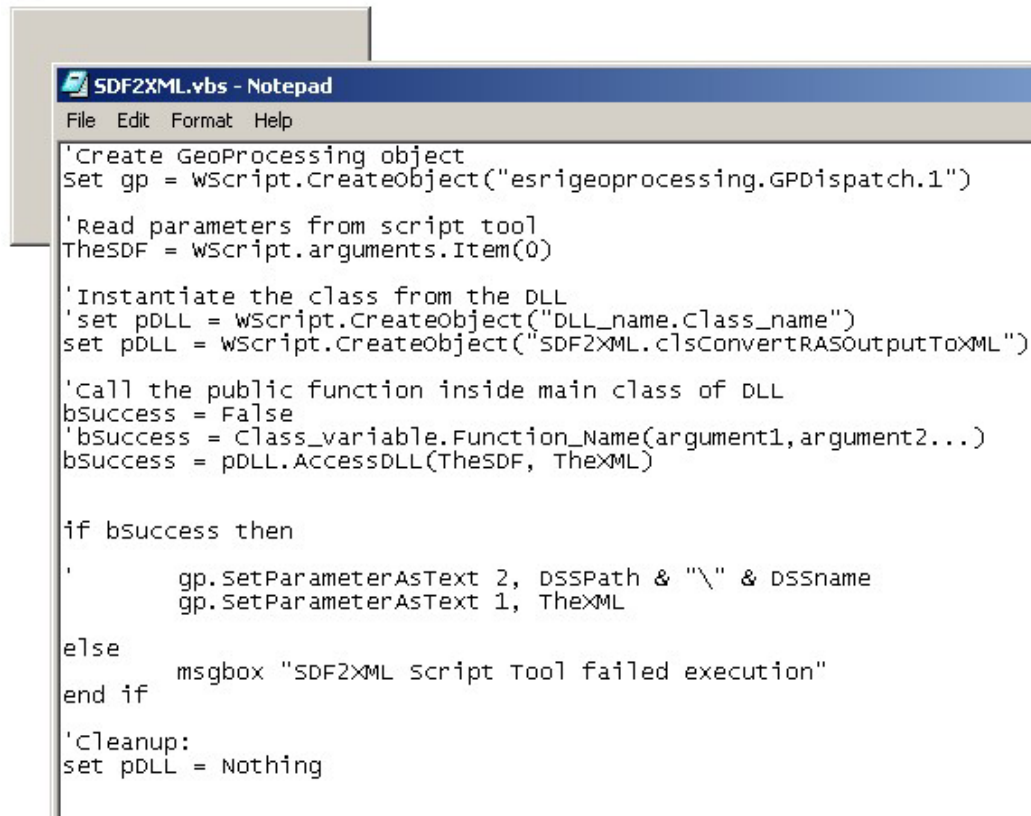
Model: ReplaceTable

Toolset: Components

Model: SDF2XML

Toolset: Scripts

Name: **SDF2XML**
Type: **Toolbox Tool**

```
SDF2XML.vbs - Notepad
File  Edit  Format  Help

'Create GeoProcessing object
Set gp = WScript.CreateObject("esrigeoprocessing.GPDispatch.1")

'Read parameters from script tool
TheSDF = WScript.arguments.Item(0)

'Instantiate the class from the DLL
'set pDLL = WScript.CreateObject("DLL_name.Class_name")
set pDLL = WScript.CreateObject("SDF2XML.clsConvertRASOutputToXML")

'Call the public function inside main class of DLL
bSuccess = False
'bSuccess = Class_variable.Function_Name(argument1,argument2...)
bSuccess = pDLL.AccessDLL(TheSDF, TheXML)


if bSuccess then

'        gp.SetParameterAsText 2, DSSPath & "\" & DSSname
         gp.SetParameterAsText 1, TheXML

else
         msgbox "SDF2XML Script Tool failed execution"
end if

'Cleanup:
set pDLL = Nothing
```

Model: XMLtoXSElev

Toolset: Scripts

Name: **XML2XSElev**
Type: **Toolbox Tool**

XML2XSElev.vbs - Notepad

File   Edit   Format   Help

```
'Create GeoProcessing object
Set gp = WScript.CreateObject("esrigeoprocessing.GPDispatch.1")

'Read parameters from script tool
XMLFile = WScript.arguments.Item(0)
XSLayer = WScript.arguments.Item(1)
StreamIDFld= WScript.arguments.Item(2)
ReachIDFld= WScript.arguments.Item(3)
StationFld= WScript.arguments.Item(4)


'Instantiate the class from the DLL
'set pDLL = WScript.CreateObject("DLL_name.Class_name")
set pDLL = WScript.CreateObject("XMLtoXSElev.clsXMLtoXSElev")

'Call the function from the class
bSuccess = False
'bSuccess = Class_variable.Function_Name(argument1,argument2...)
bSuccess = pDLL.UpdateElevs(XSLayer, StreamIDFld, ReachIDFld, StationFld, XMLFile)

if bSuccess then
        gp.SetParameterAsText 5, XSLayer
end if
```

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References

ESRI, 2003. ArcSDE Information. Internet Site:
<http://www.esri.com/software/arcgis/arcinfo/arcsde/>

Gopalan, H., D. Maidment. 2003. *WRAPHydro Data Model: Finding Input Parameters for the Water Rights Analysis Package.* CRWR Online Publication 03-3. <http://www.crwr.utexas.edu/online.shtml>

Halff & Associates. 2002. *Colorado River Flood Damage Evaluation Report.* Fort Worth, Texas.

Hydraulic Engineering Center (HEC). 2003. CWMS Website. U.S. Army Corps of Engineers. <http://www.hec.usace.army.mil/cwms/cwms.html>

Lower Colorado River Authority (LCRA). 1998. *LCRA Marks One-Year Anniversary of Near-Record Flood while Monitoring Region's Dry Conditions.* Internet Site Press Release: <http://static.lcra.org/newsarchive/1998/06/flooddry.htm>

Maidment, D. R. 2002. Arc Hydro – GIS for Water Resources. ESRI Press. Redlands, California.

McKinney, D. and Cai Ximing. 2002. *Linking GIS and Water Resources Models: an Object-Oriented Method.* Environmental Modeling and Software, Vol. 17, pp. 413-425.

National Research Council. 2000. *Risk Analysis and Uncertainty in Flood Damage Reduction Studies.* National Academy Press, Washington, D.C.

Noman, S., E.J. Nelson, A. Zundel. 2001. *Review of Austomated Floodplain Delineation from Digital Terrain Models*. Journal of Water Resources Planning and Management. Nov/Dec, Vol. 127, No. 6, pp. 394-402.

Robayo O., T. Whiteaker, D. Maidment. 2004. Converting a NEXRAD Map To a Floodplain Map. Submitted to AWRA Spring Specialty Conference.

Schneider, K. 2002. ArcBASINS: A GIS Model for the BASINS Database. CRWR Online Publication 02-5. <http://www.crwr.utexas.edu/online.shtml>

Stone, S. and D. Maidment. 2001. *Geospatial Database and Preliminary Flood Hydrology Model For the Lower Colorado River Basin.* CRWR Online Publication 01-4. <http://www.crwr.utexas.edu/online.shtml>

USGS, 2003. *National Hydrography Dataset*. Internet Site: <http://nhd.usgs.gov/>

Vita

Daniel Redd Obenour, the son of James and Martha Obenour, was born in Oberlin, Ohio on February 7th, 1979. Dan graduated with honors from Wellington High School in 1997, and received his B.S. in Civil Engineering from the University of Akron, Ohio in 2002. Throughout his college years, Dan gained technical experience working for a civil engineering consulting firm in Akron, Ohio; and for the U.S. Public Health Service at various locations throughout the country. He entered the University of Texas at Austin in the fall of 2002. After graduation, Dan will ride a bicycle from Austin, Texas to Anchorage, Alaska to raise money and awareness for the fight against cancer. Once this journey is completed, he will begin his professional career at Freese and Nichols, Inc. in Austin, Texas.

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This thesis was typed by the author.